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MOTION-INDUCED INTERRUPTIONS AND POSTURAL EQUILIBRIUM IN LINEAR LATERAL ACCELERATIONS

by

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14. ABSTRACT
The scope of this applied research was to conduct an experiment using a motion simulator in order to (a) revisit the relationship between sway parameters and Motion-Induced Interruptions (MIIs) in a controlled environment, and (b) focus on the effect of the frequency (period) of the acceleration stimulus on MII occurrence.

This study assesses lateral tipping, as opposed to sliding, MIIs of standing persons in a simulated motion environment representing dry deck conditions. Results verify previous findings that MII occurrence increases with increasing peak sway acceleration. Although MII occurrence was associated with the frequency of the motion stimulus, the effect is not as clear as that of acceleration. Overall, results suggest that complex, multidirectional motions create more tipping MIIs than unidirectional motion. Beyond acceleration, MII research also should incorporate frequency characteristics and motion complexity as factors influencing MII occurrence.

In this study, we introduce the "probable" MII, a novel term referring to a slight, temporary loss of balance without tipping. This term fills the gap between the theoretical definition of an MII and a human-centered perception of an MII, where loss of balance is not a binary phenomenon. From a human performance perspective, the investigation of the "probable" MIIs may be of a value because they are more common than the "definite" MIIs (depending on the motion profile, this difference ranged from 16% to 67%).

As a result of these findings, we developed a mathematical model of MII occurrence based on the amplitude and period of motion stimulus acceleration. The model assumes an additive combination two functions: a generalized logistic associated with the amplitude of acceleration and a Gaussian for period. The developed model approximated the observed MIIs with good results (< +/– 9% difference).

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I. INTRODUCTION

A. GENERAL

The effects of environmental stressors on the structure, the crew, and the passengers of naval vessels must be considered as part of a systems engineering approach to ship design. Ship motions, especially in higher sea states, limit a crews' ability to perform essential command, control, and communications functions; navigation tasks; maintenance responsibilities; and even the preparation of food (Stevens & Parsons, 2002). Seakeeping analyses seek to determine the effects of vessel motion on operational performance (Graham, Baitis, & Meyers, 1992). We concur with Colwell's (1989) comment that ". . . the goal of work on human performance in the naval environment is to develop methods and criteria which permit quantitative analysis of human performance and its degradation due to motion-induced problems" (p. 1).

In the 1980s, researchers, engineers, and naval architects from the David W. Taylor Naval Ship Research and Development Center (now Naval Sea Systems Command Carderock Division – NSWC CD) identified Motion Induced Interruptions (MIIs) to be an important contributing factor to operational readiness at sea (Applebee, McNamara, & Baitis, 1980; Baitis, Applebee, & McNamara, 1984; Baitis, Woolaver, & Beck, 1983). As stated by Crossland and Rich (1998), excessive ship motion in rough weather will impair the fighting ability of a warship and degrade the crew's ability to operate the ship's systems. Initially, an MII was defined as an incident where a person slips, slides, or loses their balance (Baitis et al., 1984; Crossland & Lloyd, 1993; Graham, 1990; Graham et al., 1992). Later, other researchers extended the initial definition by including task interruption. Crossland (2005) described an MII as an incident where ship motions become sufficiently large to cause a person to slide or lose balance unless they temporarily abandon their allotted task to pay attention to keeping upright.

The integration of task interruption with the biodynamic effect of a ship's motion was covered in the following definition intended for sailors being invited to participate in an MII research project (McCauley, Matsangas, & Miller, 2005, p. 4).

> MIIs are all kinds of duty interruptions caused by ship's motion. If standing, an MII could be sliding, losing balance, not being able to walk, or having to grab hold of anything firm so as to continue conducting a task. If seated, an MII could be holding on to a chair to prevent sliding, holding on to a console to continue watching the scope, or unusual difficulty in using the keyboard or other controls due to ship's motion. In general, whenever the ship's motion is making an individual stop what he/she is doing, even for a short amount of time, it is an MII.

Crew safety and performance aboard ship requires that the human be able to maintain postural equilibrium and to avoid slips, trips, and falls induced by deck motion. Graham (1990) noted that the ability of personnel to keep their balance on the deck of a conventional-hull vessel is limited by the combination of deck inclination (pitch or roll) with lateral or vertical accelerations.

Conceptually, MII research can be divided into two periods. The first one spans from the mid-80s to the mid-90s. It includes establishing the MII field of research (Baitis et al., 1984; Baitis et al., 1983), and the development of the rigid-body approach (Graham, 1990; Graham, Baitis, & Meyers, 1991; Graham et al., 1992).

Initially, the rigid-body approach was based on the lateral force estimator (LFE) to estimate the occurrence of MIIs from lateral forces acting on the human body (Baitis et al., 1984). Later, Graham (1990) introduced the generalized LFE (GLFE), and extended model predictions in the frequency domain. The GLFE extended the utility of the model to combinations of lateral and vertical accelerations, whereas the frequency domain approach permitted the calculation of the number of MIIs per unit time (Graham, 1990; Graham et al., 1991). In 1992, an extension of the MII model included the effect of wind and longitudinal forces (Graham et al., 1992).

Baitis and colleagues (1984) reported that lateral (y-axis) linear accelerations, also known as "sway," were the most important contributors to MII and they offered preliminary predictions about the level of acceleration that would induce MIIs. The basis of these predictions is not clear. They also provided quantitative estimates of MII severity, as shown in Table 1.

Table 1. Predicted MII outcomes for various levels of lateral linear “sway” acceleration (adapted from Baitis et al., 1984, p. 193, Fig. 3)

Predicted Outcome	***Acceleration (g)***
Possible MII	0.08 – 0.10
Probable MII	0.10 – 0.12
Serious MII	0.12 – 0.14
Severe Limitations	0.14 – 0.16
Extremely Hazardous	above 0.16

Subsequent research confirmed that sway and roll are critical components of MII development (Crossland & Lloyd, 1993). Beyond performance deterioration and biodynamic problems, MIIs have also been associated with increased risk for musculoskeletal injuries (MacKinnon, Matthews, Holmes, & Albert, 2011/2012).

During the second period of MII research, subsequent research efforts identified gaps in the rigid body approach and started the development and investigation of more complex, articulated dynamic models, mimicking more closely the actual attributes of the human system.

One of the issues associated with the rigid-body model is the “over-prediction” problem (Crossland & Rich, 1998; McCauley, Pierce, & Matsangas, 2007; Wedge & Langlois, 2003). The “Graham Tipping Equations,” as well as consequent formulations of the initial model, were based on the pioneering Carderock analyses and a strictly physical prediction of tipping over or sliding as a consequence of acceleration. The MII model assumes that the human acts like a rigid body (Graham, 1990; Graham et al., 1992). Therefore, this model does not take into account the ability of the human to predict motions and compensate by shifting their weight, adjusting their center of gravity, etc.

Analyses of MIIs have extended the Carderock research by addressing the dynamics of human balance and postulating a multiple inverted pendulum model for the dynamics of human postural control (Langlois, 2010; Wedge & Langlois, 2003).

As already noted, two kinds of MIIs were defined in the conventional approach (Baitis et al., 1984): tipping and sliding. Baitis et al. (1984) noted that higher friction coefficients between the shoe of the standing person and the deck would lead to tipping, whereas smaller friction coefficients would lead to sliding MIIs.

B. MIIS VERSUS MOTION AMPLITUDE AND FREQUENCY

The central role of acceleration in postural responses, and the association between acceleration and MIIs, is known and well established in the literature (Baker & Mansfield, 2010; Brown, Jensen, Korff, & Woollacott, 2001).

The effect of frequency (or period) on MII occurrence, however, is not clear. Sari and Griffin (2009) conducted a study with walking participants reporting their estimates of losing their balance while they were in a low frequency (0.5 to 2 Hz) lateral oscillation environment. Within the 0.5 Hz to 2 Hz range, they concluded that the probability of losing one's balance decreased as the frequency increased, and that the highest incidence of MIIs was found at approximately 0.5 Hz. A study by Nawayseh and Griffin (2006) found that standing people had increased balance problems at low frequencies (0.125 Hz to 0.5 Hz) compared to higher frequencies (0.5 Hz to 2 Hz). These results contradict other studies concluding that increased frequency leads to increased biodynamic problems for standing or walking persons (Bles, Nooy, & Boer, 2002; Crossland & Lloyd, 1993). Experiments conducted at the U.S. Naval Biodynamics Laboratory (NBDL) found that the effect of frequency on MIIs depends on the direction of the human body compared to a ship's axes (Crossland, Colwell, Baitis, Holcombe, & Strong, 1994; Crossland & Lloyd, 1993). Based on their MII findings on various tasks, the researchers suggested that low frequency motion profiles create fewer biodynamic problems.

Motion complexity also is associated with MII occurrence. The finding that complex, multidirectional motions create more tipping MIIs than simple, linear motions (e.g., single-axis motions) has been attributed to the unpredictability of complex motions. The more complex a motion profile, the more difficult it is for the human to predict and compensate for it (Crossland, 2005; Horak & Nashner, 1986).

Lastly, the relative direction of motion, compared to the human body stance, affects MII occurrence. For a person facing forward or aft, the roll component significantly reduces standing or walking balance (Bles et al., 2002; Crossland & Lloyd, 1993; Wertheim, Heus, & Vrijkotte, 1994). Another study, however, found conflicting results. In a simulated ship-motion study, participants were performing manual material handling tasks (Holmes et al., 2005; Matthews, MacKinnon, Albert, Holmes, &

Patterson, 2007), and results showed that pitch motion had a significantly more adverse effect on MII occurrence, compared to roll or quartering motions.

C. BALANCE AND BODY MASS

In general, the relationship between body weight and balance is supported by studies of human balance control and gait. Research assessing static balance, postural sway, or walking at self-selected speed has found that increased body weight and Body Mass Index (BMI) have a negative effect on postural stability (Greve, Cuğ, Dülgeroğlu, Brech, & Alonso; Hue et al., 2007; Ku, Abu Osman, Yusof, & Wan Abas, 2012; Southard, Dave, & Douris, 2010).

D. BALANCE AND BASE OF SUPPORT

Loss of balance is associated with the base of support of the human body in the direction of movement (Nawayseh & Griffin, 2006). To maintain balance, the standing person controls the position of the trunk, i.e., the body’s center of mass located in the trunk (Buchanan & Horak, 1999). Theoretically, stability is ensured when the center of mass lies within the base of support (e.g., stance width). Research, however, has also identified the functional stability region (FSR), which is the psychophysical portion of the base of support, where individuals ensure that their center of gravity lies within (Holbein & Redfern, 1997; McDermott, Shaw, Demchak, & Holbein, 2005).

E. LEARNING TO COMPENSATE FOR MOTION

Postural stability adaptation is a phenomenon investigated in current research literature. Adaptation to the vestibular stimulus has been observed in body sway induced by galvanic stimulation of the vestibular nerve and labyrinth. A postural adaptation time constant was identified in the range of 40-50 seconds (Johansson, Magnusson, & Fransson, 1995). Adaptation also has been observed in the amplitude of the center of pressure in a lateral motion environment, with the amplitude decreasing over repeated exposures (Buchanan & Horak, 1999). Another study investigated support surface rotations and identified a generalized habituation in the postural control system (Keshner, Allum, & Pfaltz, 1987).

In previous field research, the results did not reveal midterm (in the order of two days) MII adaptation to ship motion (McCauley & Matsangas, 2005; McCauley et al., 2005). However, a long-term adaptation effect for MIIs—perhaps on the order of months or years—has been observed (McCauley, Pierce, Matsangas et al., 2007). The researchers noted that:

> It is likely that more sea experience leads to relatively automatic compensation for mild motion effects that contribute to MIIs. . . . at-sea experience builds long term adaptation for maintaining postural stability, locomotion, and countering interference with manual tasks despite motion perturbations. (McCauley, Pierce, Matsangas et al., 2007, p. 55)

F. TIPPING COEFFICIENT

The tipping coefficient is a critical component of the legacy (Carderock) MII model. The tipping coefficient defines the threshold for when an MII will occur. The lower the tipping coefficient, the harder it is to maintain balance (Crossland & Rich, 1998). The coefficient, expressed as the estimated number of MIIs per minute, provides a metric to evaluate the probability of tipping during a given time period. It is interesting to note Crossland and Lloyd's (1993) comment that "the ability to predict 'on average' the number of MIIs expected on a particular design of ship in a variety of run conditions is sufficient for the ship designer" (p. 1).

The tipping coefficient for body-lateral MIIs is defined as the ratio of half the stance width (including shoe width) (***l***) over the height (***h***) of the Center of Gravity (CG), as depicted in Figure 1 (Crossland & Lloyd, 1993; Graham, 1990).

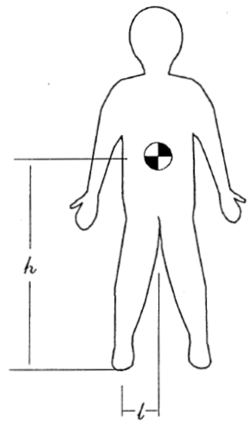


Figure 1. Model of a person facing forward or aft (from Graham, 1990, p. 67)

Crossland and Lloyd (1993) identified three methods to derive the tipping coefficient:

- By measuring the physical dimensions of the participants (“theoretical”). Based on this method, Graham (1990) used the representative values of h=0.91 m and l=0.23 m, which lead to a value of 0.25 for the tipping coefficient appropriate to lateral MIIs. This value was verified by Crossland and Lloyd (1993), who found that, for lateral MIIs, the theoretical and global estimates were very consistent, in the range 0.25 to 0.27.
- By counting the total number of MIIs in each run and finding the value of the tipping coefficient required to yield that result (the “global” tipping coefficient). This metric is also called the “empirical” method (Crossland & Rich, 1998).
- By examining each MII and estimating the value of the tipping coefficient from the records of the ship motions experienced at that time (the “instantaneous or local” tipping coefficient).

Crossland and Lloyd (1993) calculated the global tipping coefficient over the entire session of MIIs by comparing the predicted and observed number of MIIs. The derived global tipping coefficients for standing and facing fore/aft, or athwartships, compared well with Graham’s (1990) estimations of the tipping coefficients. Based on their results, the authors postulated that all the MIIs are roll driven (Crossland & Lloyd, 1993). It should be noted, however, that these experiments were conducted with a simulator that could not create sway motion.

G. SCOPE

The scope of this study is to conduct a simulated motion experiment in order to (a) revisit the relationship between sway parameters and MIIs in a controlled environment, and (b) focus on the effect of the frequency (period) of the acceleration stimulus on MII occurrence.

II. METHODOLOGY

A. EXPERIMENTAL DESIGN

The initial design was based on our belief that, for inducing MIIs, the important motion variables are:

- Axis.
- Acceleration level.
- Period of the acceleration stimulus.

We examined the lateral (sway) motion with the participants facing forward. Close reading of the Carderock literature actually suggests that the regions slightly "aft" of 90 degrees and 270 degrees might be the most likely to induce MIIs. For simplicity, we chose to use 90 and 270 because they are cardinal compass points and relatively close to the maxima suggested by earlier research (Baitis et al., 1984).

Our initial partial factorial design varied acceleration, as per Table 2, from 0.08 g to 0.16 g (input command levels of acceleration to the motion base). While we had no previous data on which to base the range of time (duration) of the acceleration, it became obvious that the simulator's horizontal displacement limit was a major constraint. Even at the lowest level of acceleration (0.08 g) in the initial protocol, we were unable to achieve a two-second duration without hitting the "stops." According to our calculations, the "X" entries in Table 2 indicate that the motion conditions, defined by the combination of acceleration level and the time period of the acceleration, could NOT be achieved because of the displacement limits of this motion platform.

Table 2. Initial factorial design

Acceleration (g) (peak)	***Period (sec)*** 0.5	1.0	1.5	1.25	1.65
0.08					
0.10					X
0.12			X	X	X
0.14			X	X	X
0.16		X	X	X	X

The final definition of the motion conditions will be given later in this section because the initial exploratory investigation (see Appendix E) provided data that fed-back to revision of the experimental design.

In conjunction with the sway motion, three other motion conditions were introduced—pitch, roll, and pitch + roll. In each case, the motion was a continuous, sinusoidal oscillation, defined by the angular displacements and sine wave periods shown in Table 3.

Table 3. Definition of the angular motion conditions

Condition	***Angular Displacement (deg)***	***Period (sec)***
Pitch	+/– 6	8
Roll	+/– 5	8
Pitch + Roll	Pitch +/– 6	8
	Roll +/– 5	7

The change in period (seven seconds) for the Roll in the Pitch + Roll condition was to avoid a time-locked relationship between the pitch and roll axes. The sway acceleration was initiated from the left or right in a sequence that was not easily predictable by the participant. The sway motion was initiated at one of three times relative to the angular motion—at full left, center (flat), or full right roll, or for pitch at full pitch down, level, or full pitch up.

B. PARTICIPANTS

The Participants were recruited by convenience from the military and civilian staff population working at the Naval Surface Warfare Center Panama City Division (NSWC-PCD). No rewards or inducements were given. A job number was provided that could be used in the NSWC-PCD accounting system to charge their labor time (two hours) for participating in this research.

Initially, 22 individuals participated in the study. For each Participant, the available data are shown in Appendix A. Data analysis was based on 20 Participants. Participant 2902 was excluded because of lack of data. In order to have five Participants per motion condition, we randomly selected Participant 3102 to be excluded from the analysis.

C. EQUIPMENT AND INSTRUMENTS

1. Vicon Motion Capture System

A Vicon motion capture system was set up with seven cameras to measure body position and movement of the Participants. The Participants wore a body suit embedded with over 50 reflectors to support the body-motion analysis.

A full report of the data from the motion capture system will be submitted separately.

Figure 2. Researcher wearing the motion capture suit with IR reflectors

2. Motion Base

This study was made possible by the use of a MOOG 6DOF5000 motion platform that had the capability to produce motion in six degrees of freedom (pitch, roll, yaw and heave, surge, and sway), with a payload up to 5,000 pounds.

Figure 3. A MOOG 6-DOF motion base similar to the one used in this study

This platform is a "synergistic hexapod" or "Stewart Platform" motion base, similar to those used with many flight simulators. There were, however, some limitations with the use of this motion platform for our purposes; namely, the maximum lateral displacement was +/– 14.4 inches. Acceleration levels of up to 0.75 g were possible with this motion platform, but that relatively high level of acceleration could only be applied for a very short time (on the order less than one second) before the displacement limit was reached.

3. Motion Sensors on the Platform

Motion sensors were affixed to the motion platform to provide an independent check on the actual levels of acceleration produced by the equipment. The cabin was removed and a padded hand-rail was installed on all four sides of the platform. The setup was similar to a small boxing ring, with the ropes on four sides being equivalent to the padded handrails.

4. Study Questionnaires

Participants completed two questionnaires. The pretest questionnaire was administered before the data collection and was used mainly for screening. Participants answered whether they had been diagnosed with vestibular or other disorders, or injuries that could affect their performance in the experiment. Participants also provided information regarding their usual state of fitness, medication use, alcohol and caffeinated drinks consumption, basic demographic information, and completed the Motion Sickness Assessment Questionnaire (MSAQ). The posttest questionnaire included questions regarding the severity of MIIs during the test, and the MSAQ. The study questionnaires are included in Appendix A.

5. MSAQ

The Motion Sickness Assessment Questionnaire (MSAQ) is used for the assessment of motion sickness severity (Gianaros, Muth, Mordkoff, Levine, & Stern, 2001). The MSAQ includes 16 symptoms leading to four subscales (Gastrointestinal, Central, Peripheral, and Sopite-related). The linear combination of the subscale scores leads to the overall motion sickness score. The MSAQ has been used in a number of NPS field studies with good results (McCauley & Matsangas, 2005; McCauley et al., 2005; McCauley, Pierce, & Matsangas, 2007; McCauley, Pierce, Matsangas et al., 2007).

The utility of MSAQ in this study is based on the nonspecificity associated with motion sickness symptoms (Wiker & Pepper, 1978). Symptoms associated with motion sickness, such as headache or fatigue, also can be observed in the absence of a nauseogenic stimulus for any number of reasons. Drowsiness, headache, and general discomfort sometimes will exist even in static/dockside conditions (Wiker & Pepper, 1978). Therefore, we used MSAQ to collect ratings for the 16 symptoms as a check that motion sickness symptoms were not being introduced by the motion environment of this study.

6. Sharpened Romberg Test

The Sharpened Romberg test assesses postural instability (Lanska & Goetz, 2000; Wilkins & Brody, 1968). The Participant stands with arms folded across their chest, and feet in a heel-to-toe position. They are instructed to close their eyes and hold this position for 30 seconds, while postural sway is assessed. The time-to-balance failure was recorded using stopwatch. A positive test was indicated by the Participant’s failure in any one of three criteria: keeping the eyes closed, a loss of balance requiring the feet to move, or the inability to maintain the arms across the chest.

D. PROCEDURES

This research proposal was approved by the Naval Postgraduate School Institutional Review Board (IRB). Data collection was conducted at NSWC-PCD in late October and early November 2012.

Initially, the Participants were informed of the purpose of the study and their right to terminate their participation at any time without consequence. They donned a special suit with embedded reflectors to enable body motion measurement via the Vicon motion capture system. After completing the initial paper surveys, the Sharpened Romberg test was administered. The Participants were escorted onto the motion platform, where they donned a safety harness that was clipped onto an overhead beam to ensure their safety.

Figure 4. Participant on the motion platform wearing the reflector suit and facing "forward"

The Participants were instructed to place their feet approximately shoulder-width apart at the center of rotation of both the pitch and roll axes (at the longitudinal axis of the "ship") facing "forward." For each Participant, initial foot position was marked on the platform to ensure a consistent foot position within and across trials. While on the motion platform, the participants had full vision of the interior of the lighted room. No cognitive tasks were assigned. Their only instruction was to stand normally, knees slightly bent, hands relaxed at their side, and eyes open. After each sway event, the Participant provided a rating on a 1-5 scale to indicate the intensity of the motion event, where 1 was benign (barely noticeable) and 5 was "intense" and difficult or nearly impossible to maintain balance.

A researcher was located in the same room keeping a log of MIIs and comments regarding the MIIs or other interesting information. Each Participant was on the motion platform for approximately 60 minutes, during which they participated in four motion conditions. One motion condition included only the transient motion component, sway (lateral, Y-axis) acceleration, whereas the rest of motion conditions included a combination of the transient sway component superimposed on nontransient, angular oscillations (Sway only, Pitch + Sway, Roll + Sway, Pitch + Roll + Sway).

The main trigger for the MII is whole body sway motion. The waveform of the sway was characterized as a one-cycle oscillation from position A to B to A. The peak acceleration specified for each "sway trial" was equal in the two directions (A to B and the immediate return B to A). The period of each trial was the period of a sine wave with one full cycle of displacement (A to B to A). In each case, a "trial" was one sway acceleration, either alone ("Sway Session") or in addition to one or more continuous angular oscillations (Pitch or Roll) defined later in this Section. The order of the four sessions was changed by starting each Participant on the next of the four conditions (the first Participant started with Sway Session, the second Participant started with the Pitch-Sway Session, etc.). Participant numbers were coded by the date and arrival sequence. The Participant was on 1 November, so the number was 0101; the second Participant for that day was 0102, and so on. A five-minute break was scheduled after the first two sessions. There were 120 motion trials per one-hour experimental session.

1. Sway-Only Motion Session

Each sway-only motion session included 32 trials. The trials consisted of two iterations of each cell in the following matrix ("√" means that the corresponding data exist). Trials 17 to 32 are repeating the motion attributes of trials 1 to 16. The two iterations were not consecutive, but rather a sequence throughout the entire matrix twice. The motion combinations of the sway amplitude acceleration and period are shown in Table 4 (input command levels of acceleration to the motion base).

Table 4. Sway-only motion parameters

Peak Acceleration [g]	***Period [sec]*** 1.00	1.50	1.75	2.00
0.12				√
0.14				√
0.16	√	√	√	√
0.18				√
0.20	√	√	√	
0.24	√	√	√	
0.28	√	√	X	

The cell with an "X" was not feasible due to the platform displacement limits, so a combination of 0.28 g and a 1.5-second period was used instead. Motion characteristics in each trial are shown in detail in Appendix C. The initiation of the sway trials occurred at an unpredictable time, depending primarily on the time required to enter the data into the motion platform control system for the next trial. The average intertrial interval was 17.6 seconds (SD=3.11, MD=17.1).

2. Pitch and Sway Motion Session

The 32 sway trials were superimposed on a sinusoidal pitch oscillation, with an angular displacement of +/– 6 degrees and a period of 8 seconds. The sway acceleration was initiated at one of three angular positions of the pitch motion—full pitch down (–6 degrees), full pitch up (+6 degrees), and horizontal (0 degrees). The motion combinations of the sway amplitude acceleration and period are shown in Table 5 (input command levels of acceleration to the motion base).

Table 5. Sway combinations within the Pitch + Sway motion condition

Peak Acceleration [g]	***Period (sec)*** 1.50	1.75	2.00
0.16	√	√	
0.18			√
0.20	√	√	
0.24	√	√	
0.28	√	X	

The cell with an “X” was not feasible due to the platform displacement limits, so a unique combination of 0.18 g and a 2.0-second period was used instead. Motion characteristics in each trial are shown in detail in Appendix C. The average intertrial interval was 32.3 seconds (SD=7.15, MD=32.1).

3. Roll and Sway Motion Session

The 32 sway trials were superimposed on a sinusoidal roll oscillation, with an angular displacement of +/– 5 degrees and a period of 8 seconds. The sway acceleration was initiated at one of three angular positions of the roll motion—full left (–5 degrees), full right (+5 degrees), and horizontal (0 degrees). The motion combinations of the sway amplitude acceleration and period are shown in Table 6 (input command levels of acceleration to the motion base).

Table 6. Sway combinations within the Roll + Sway motion condition

Peak Acceleration [g]	***Period (sec)*** 1.25	1.50
0.16	√	√
0.20	√	√
0.24	√	√
0.28	√	√

Motion characteristics in each trial are shown in detail in Appendix C. The average intertrial interval was 32.3 seconds (SD=7.14, MD=32.1).

4. Pitch, Roll, and Sway Motion Session

The 24 sway trials were superimposed on two sinusoidal motions: a roll and a pitch oscillation combined. The motions for this session were based on the partially factorial combination of the motions in the previous sessions:

- Pitch = +/– 6 degrees with a period of 8 seconds.
- Roll = +/– 5 degrees with a period of 7 seconds.

The roll period differed from the previous session because we wanted to avoid synchronizing the roll and pitch periods.

The motion combinations of the sway amplitude acceleration and period are shown in Table 7 (input command levels of acceleration to the motion base).

Table 7. Sway combinations within the Pitch + Roll + Sway motion condition

Peak Acceleration [g]	***Period (sec)*** 1.00	1.75	2.00
0.14			√
0.16	√	√	
0.18			√
0.24		√	
0.28	√		

Motion characteristics in each trial are shown in detail in Appendix C. The average interval between trials was 27.9 seconds (SD=6.20, MD=28.1).

5. External Validity of Motion Profiles

The simulated motion profiles are simple compared to the actual motion of ships at sea. We believe that the chosen profiles are a reasonable compromise between simplicity and complexity, without jeopardizing the external validity and generalizability of our findings.

First, we increased complexity gradually, from unidirectional motion (sway-only) to multidirectional (sway + pitch, sway + roll + pitch), and from simple sinusoidal (sway-only) to complex (sway + roll, sway + pitch, sway + roll + pitch). Sinusoidal motion for each motion component was used to simplify the motion complexity. Under the assumption that complex motion increases biodynamic interference (Bles et al., 2002; Crossland, 2005), using simple sinusoidal components may be a scenario with less MIIs. The motion characteristics were: sway acceleration ranged from 0.12 to 0.28 g; sway period ranged from 1 to 2 seconds; pitch angular displacement was +/– 6 degrees; roll angular displacement was +/– 5 degrees; pitch and roll period was 8 seconds, except in the sway+pitch+roll conditions, where the roll period was 7 seconds. These motion parameters are comparable to what is found in vessels like the FFG-7 frigate (Morrison, Dobie, Willems, Webb, & Endler, 1991) or in earlier MII research (Crossland & Lloyd, 1993). The duration of the motion session, approximately one hour, is comparable to that used in earlier MII research (Baker & Mansfield, 2010; Crossland & Lloyd, 1993; Crossland & Rich, 1998).

We did not include wind, longitudinal, or heave motion. The significance of wind to the development of motion interruptions was emphasized by Baitis et al. (1984). We also decided not to simulate heave because it would create changes in friction between the Participant's feet and the platform and add to the complexity of the data. Consequently, we located the Participants at the center of pitch and roll motion axes in the absence of any heave component. Furthermore, the absence of longitudinal motion is reasonable for monohull designs (Baitis, Bales, McCreight, & Meyers, 1976; Graham, 1990).

Overall, the simulated motion environment can be described as mild to moderate. The motion environment is not extreme because there was no heave motion and the limited displacement of the simulator constrained the motion events, making MIIs possible, but not inevitable. We attempted to define the motion conditions: (a) to simplify the situation, (b) to be in the realm of actual ship motion, and (c) to allow for the development of MIIs within the ability of human to compensate for biodynamic interference.

E. VARIABLES

1. Independent Variables

The independent variables of the study were the sway sinusoidal motion attributes (acceleration and period) and motion condition:

- Sway-only.
- Sway and pitch.
- Sway and roll.
- Sway combined with pitch and roll.

2. Controlled Variables

The controlled variables in the study were:

- Direction that the sway acceleration was initiated.
- For the motion conditions other than "Sway only," consideration was given to the position of the angular oscillation at the time that the sway acceleration was initiated.

- The order of motion conditions.
- The view the Participants had while on the motion platform.
- The lighting conditions in the laboratory.
- The distance between a Participant's feet while standing on the motion platform.
- The friction coefficient between shoe and deck. A gritty material, the "3M SafetyWalk," was applied to the central part of the motion platform. This material is typical for ships (e.g., LCACs).
- Participants' shoe size was measured and Participants were instructed to wear shoes with elastic soles, such as running shoes.

3. Dependent Variables

The primary dependent variable was the researcher's assessment of whether an MII occurred or not. The researcher was able to see the Participant's feet, both directly and via a video camera looking straight down on the Participant's head and feet. There were, however, certain minor movements like a slight rising of the heel that were assigned to a category of "probable." So, the researcher made a judgment on each trial, allocating the outcome of each trial to one of three MII categories—Definite, No, or Probable.

Other dependent variables were the estimation of the type of the MII (heel; step; both feet, hanging), and the Participant's estimation of motion severity (five-point Likert scale). For the record, "hanging" meant that both feet left the surface of the motion platform and the Participant was supported (briefly) by the safety harness. Based on the existing literature, the "step," "both feet," and "hanging" are defined as an MII (Graham et al., 1992). Therefore, the conventional definition of MII is included in the "Definite" MII category in this work.

F. ANALYSIS

The statistical distribution of MIIs is unknown (Crossland & Lloyd, 1993). Therefore, our analysis is based both on parametric and nonparametric methods. Analysis included the following steps:

- Demographics and analysis of the developed symptoms in motion.
- MIIs analysis (the main focus of this study).
    - Descriptive results.
    - Development of a regression model to account for the observed MIIs.
- Adaptation of MIIs over time and investigation of the association between MIIs occurrence per Participant and demographic variables.
- Analysis of the types of MIIs per motion condition and the subjective ratings of motion severity.
- Comparison with the rigid body model.

Specifically, the comparison with the rigid body model was based on the observed and the predicted incidence of MIIs. We estimated the value of the tipping coefficient for each MII. Based on the revision of the original rigid body model, we have the following equation (after Graham et al., 1992, equations 18 and 19).

$$\frac{l}{h}\left(g + \ddot{D}_3\right) < \left|-\frac{1}{3}h\ddot{\eta}_4 + \ddot{D}_2 + g\eta_4\right|,$$

where $\boldsymbol{h}$ is the height of the Participant's center of gravity**,** $\boldsymbol{\ddot{\eta}_4}$ is the instantaneous roll acceleration, $\boldsymbol{\ddot{D}_2}$ is the lateral acceleration, $\boldsymbol{g}$ is the acceleration of gravity, $\boldsymbol{\eta_4}$ is the instantaneous roll angle, $\boldsymbol{\ddot{D}_3}$ is the vertical acceleration, and $\boldsymbol{l}$ is half of the Participant's base of support. The term $(\mathbf{1/3})\boldsymbol{h\ddot{\eta}_4}$ is considered to be small for frigates and destroyers (Graham et al., 1992), and was omitted in the initial MII rigid model publications (Baitis et al., 1984; Graham, 1990). For sway-only motion, an MII occurs when the tipping estimator function is equal to or greater than the tipping coefficient.

$$\frac{\left|\ddot{D}_2\right|}{\mathrm{g}} \geq \frac{l}{h}$$

For the detection of motion characteristics leading to the development of MIIs, earlier efforts assessed the time period prior to each MII occurrence. After marking an MII, researchers evaluated the maximum acceleration within two to four seconds prior the events (Crossland et al., 2007; Crossland & Lloyd, 1993). Based on these local maxima motion conditions, the corresponding lateral tipping coefficient was calculated for each MII event. However, the motion component used for the development of MIIs in our experiment is the sway stimulus occurring on each trial. Therefore, we used an adjusted method; first, we identify the maximum lateral acceleration within each MII trial from the sensors mounted on the motion platform. If the observed lateral acceleration within each MII trial exceeds the Participant’s tipping coefficient, then the model predicts an MII. The number of predicted MIIs is then compared to the observed MIIs.

The “global” tipping coefficient was calculated by adjusting the tipping coefficient to finding the value required to yield that observed total number of MIIs.

G. DEMOGRAPHICS

Twenty healthy individuals participated in the study (14 males and 6 females). The demographics are given in Table 8.

Table 8. Demographics

Parameter	***Mean (SD, MD)***	***Minimum***	***Maximum***
Sea experience [years]	2.33 (5.92, 0.07)	0	25
Height [inches]	70.3 (2.85, 70.9)	65	76
Weight [lbs.]	193 (42.3, 188)	132	266
BMI	27.3 (4.70, 27.3)	20.3	34.9
Shoe size	MD=10	7	13
Sharpened Romberg Test (third test) [sec]	26.5 (7.65, 30)	5	30

The detailed information for height, weight, and shoe size are shown in Appendix D.

III. RESULTS

A. PRELIMINARY FINDINGS AND INSIGHTS

Before the main data collection phase of the experiment, a number of preliminary trials were conducted. Although these pre-experiment findings are incidental to the main study, we report them in Appendix E because they were surprising and potentially informative.

B. BASIC FINDINGS

First, we assess the development of 16 symptoms included in the MSAQ. The MSAQ is a standardized tool used to evaluate symptoms typically associated with the onset and development of motion sickness. These symptoms, however, can also be observed in the absence of a nauseogenic stimulus; the symptoms are nonspecific to motion sickness. In order to assess how these symptoms develop over time under the nonnauseogenic motion conditions, we collected MSAQ ratings before the commencement of the test, in the middle of the data collection session, and at the end.

As expected, the severity of symptoms was low. A one-way, within-subjects analysis of variance (ANOVA) was conducted to compare the effect of time on MSAQ indices (Total, [G]astrointestinal, [C]entral, [P]eripheral, [S]oporific). Results show that MSAQ Total, and central-related symptoms increased over time (Total: $F(2,18)=3.80$, $p=0.042$; C: $F(2,18)=4.31$, $p=0.030$), whereas gastrointestinal, peripheral, and soporific symptoms did not change (G: $F(2,18)=0.022$, $p=0.978$; P: $F(2,18)=1.74$, $p=0.203$; S: $F(2,18)=0.023$, $p=0.978$).

Next, we assessed the associations between MII occurrence and sea experience, height, weight, body mass index (BMI), feeling drowsy or tired/fatigued at the beginning of the data collection. Table 9 depicts our findings based on Spearman’s rho nonparametric correlation coefficient.

Table 9. Correlation analysis results

Parameter	MII Occurrence "Probable"	"Definite"	"Probable + Definite"
Sea experience [yrs]			
Height [in]	rho= –0.424, p=0.070		
Weight [lbs]	rho= –0.433, p=0.064		rho= –0.423, p=0.071
BMI	rho= –0.331, p=0.166		rho= –0.411, p=0.081
Shoe size	rho= –0.426, p=0.069	rho= –0.519, p=0.023	rho= –0.568, p=0.011
Feeling drowsy	rho= 0.545, p=0.016	rho=0.328, p=0.171	rho=0.451, p=0.053
Feeling tired/fatigued			rho=0.349, p=0.143

Inclusion criterion: p<0.20

We should note, however, that height, weight, BMI, and shoe size are correlated (Spearman's correlation, p<0.001). Our analysis did not identify any significant associations between MII occurrence and MSAQ indices.

C. OCCURENCE OF MIIs

During our study, we did not observe any sliding events, only tipping MIIs. These MIIs are presented in this section. For each motion condition, three figures are shown—one for "Probable" MIIs, one for "Definite," and one for the sum of "Probable" and "Definite" MIIs. Each figure demonstrates the percent of MIIs developed in the corresponding combination of peak sway acceleration (A [g]) and period (P [sec]). The percent of MIIs is calculated by dividing the number of MIIs for the given combination of A and P by the corresponding number of sway trials. For example, in the roll combined with sway motion condition, there are 80 sway trials in the 0.16 g/1.5 second combination and 12 "Probable" MIIs leading to 15% MII occurrence. Figure 5 demonstrates how tipping MII occurrence changes by peak sway acceleration (A [g]) and period (P [sec]) in Sway-only motion.

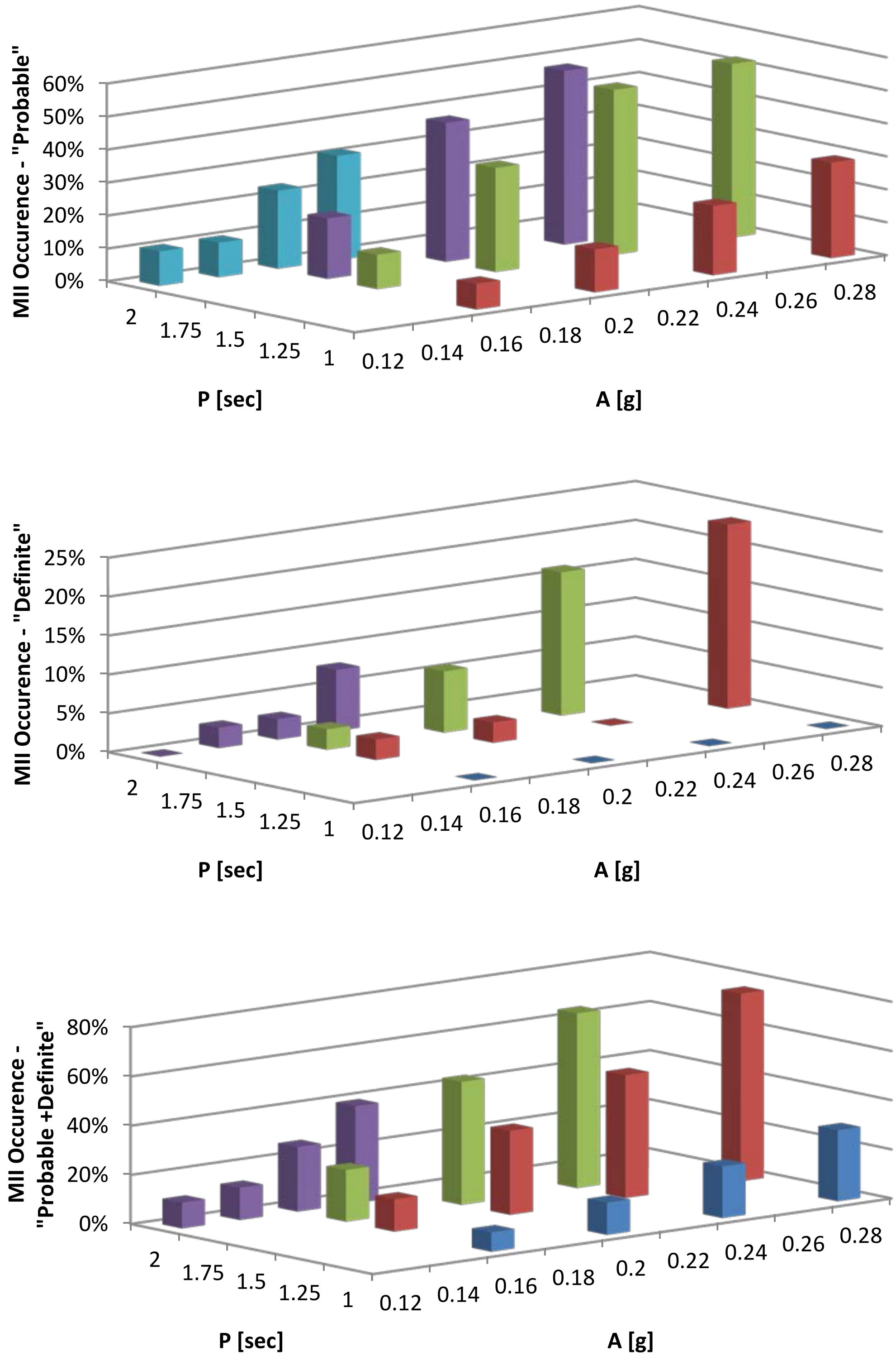


Figure 5. Sway-only motion. Three-D figures of MII occurrence ("Probable," "Definite," and "Probable + Definite") by peak sway acceleration and period

The percentage MII occurrence in Sway-only motion is consolidated in Table 10.

Table 10. MII occurrence [%] in Sway-only motion

A [g]	Period [sec] "Probable"					"Definite"					"Probable + Definite"				
	1	1.25	1.5	1.75	2	1	1.25	1.5	1.75	2	1	1.25	1.5	1.75	2
0.12					10.5					0.0					10.5
0.14					10.5					2.6					13.2
0.16	7.9		10.5	18.4	23.7	0.0		2.6	2.6	2.6	7.9		13.2	21.1	26.3
0.18					31.6					7.9					39.5
0.20	13.2		31.6	42.1		0.0		2.6	7.9		13.2		34.2	50.0	
0.22															
0.24	21.1		50.0	52.6		0.0		0.0	18.4		21.1		50.0	71.1	
0.26															
0.28	28.9		52.6			0.0		23.7			28.9		76.3		

Figure 6 demonstrates how MII occurrence changes by peak sway acceleration (A [g]) and period (P [sec]) in Sway + Roll motion.

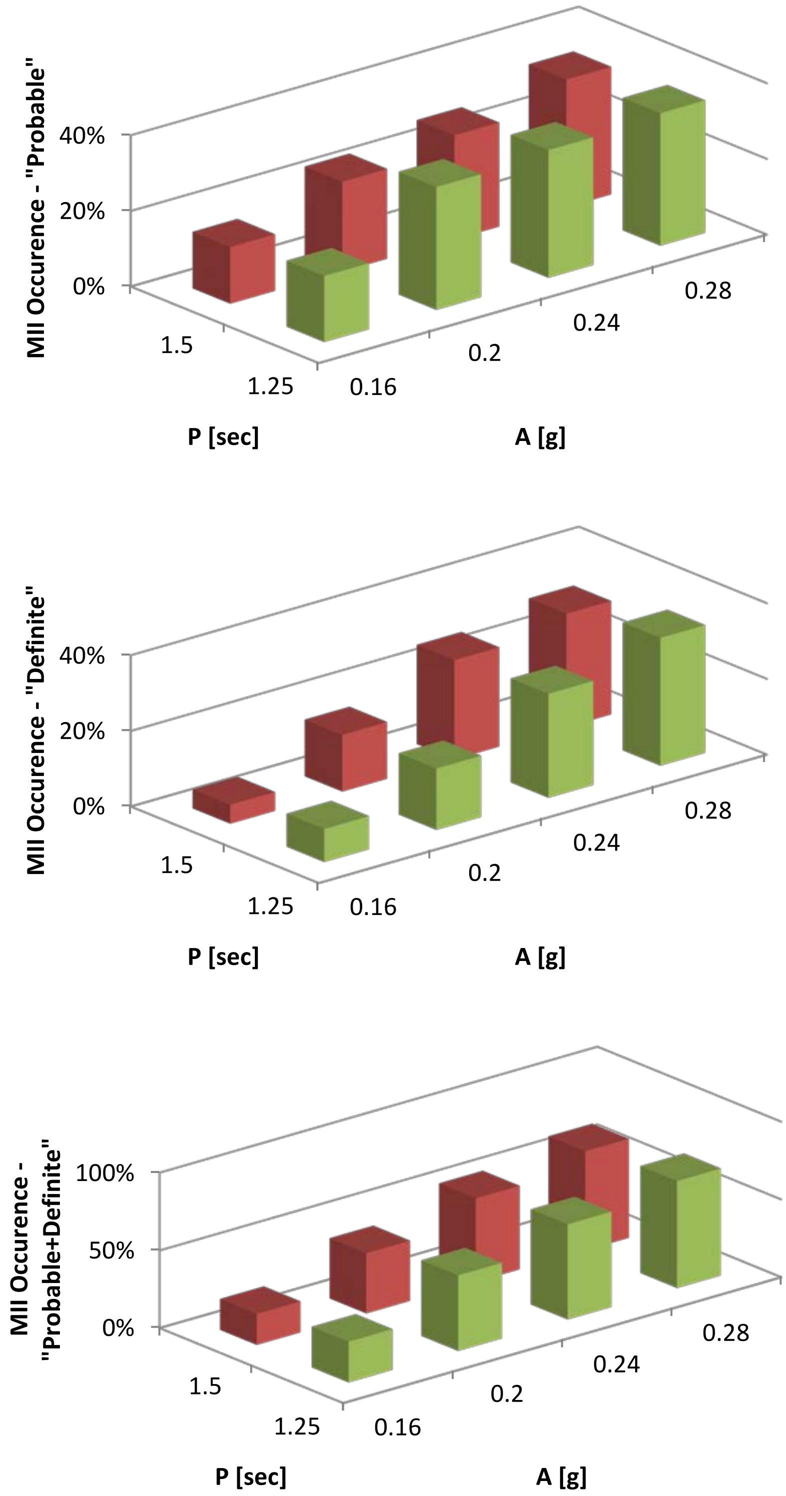


Figure 6. Sway + Roll motion. 3-D figures of MII occurrence ("Probable," "Definite," and "Probable + Definite") by peak sway acceleration and period

The percentage-wise MII occurrence in Sway + Roll motion is integrated in Table 11.

Table 11. MII occurrence [%] in Sway + Roll motion

A [g]	Period [sec]					
	"Probable"		**"Definite"**		**"Probable + Definite"**	
	1.25	1.50	1.25	1.50	1.25	1.50
0.16	17.5	15.0	8.8	5.0	26.3	20.0
0.20	32.5	23.8	16.3	15.0	48.8	38.8
0.24	33.8	27.5	27.5	26.3	61.3	53.8
0.28	35.0	33.8	33.8	30.0	68.8	63.8

Figure 7 demonstrates how MII occurrence changes by peak sway acceleration (A [g]) and period (P [sec]) in Sway + Pitch motion.

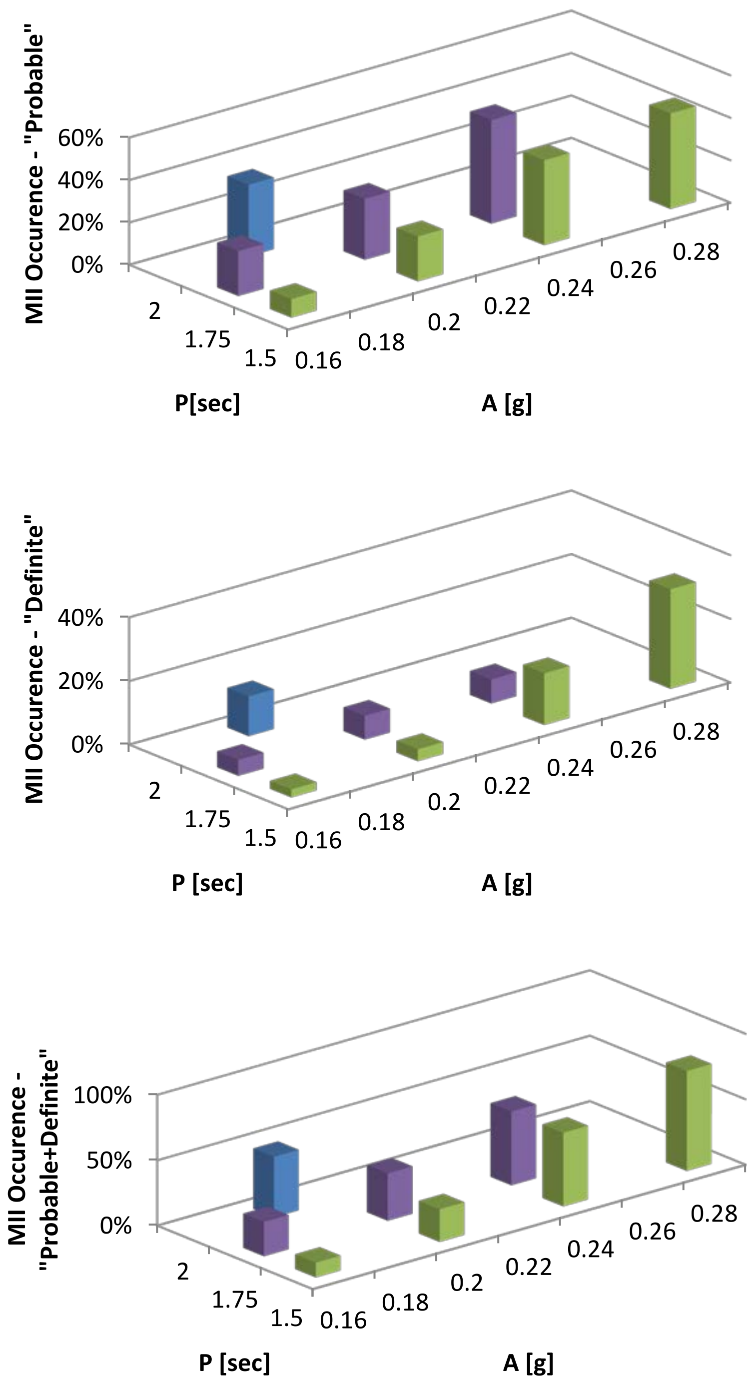


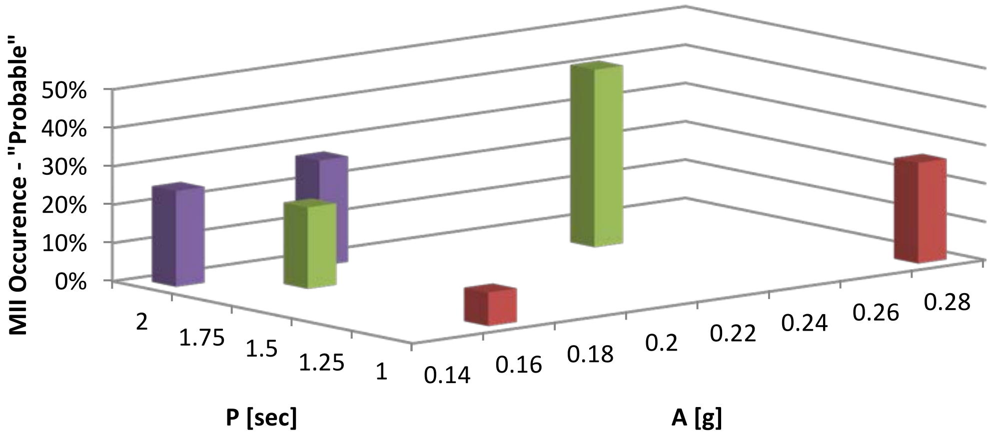
Figure 7. Sway + Pitch motion. 3-D figures of MII occurrence (“Probable,” “Definite,” and “Probable + Definite”) by peak sway acceleration and period

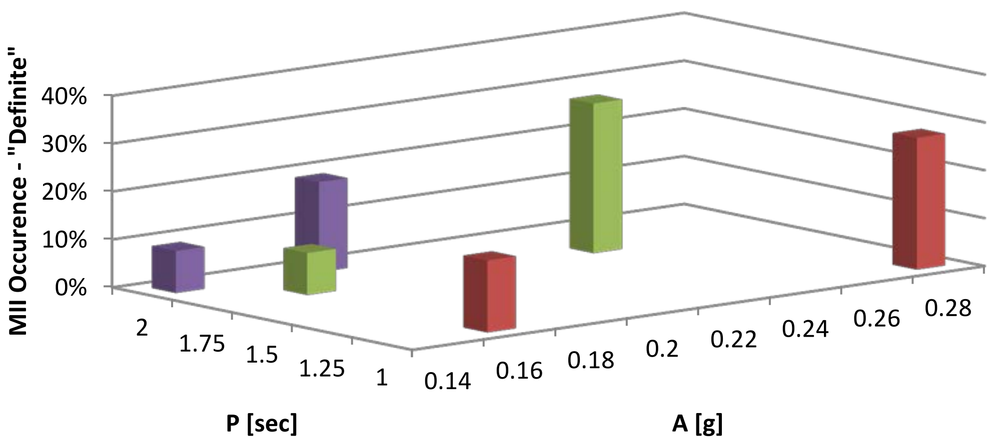
The percentage-wise MII occurrence in Sway + Pitch motion is integrated in Table 12.

Table 12. MII occurrence [%] in Sway + Pitch motion

A [g]	Period [sec]								
	"Probable"			**"Definite"**			**"Probable + Definite"**		
	1.5	1.75	2	1.5	1.75	2	1.5	1.75	2
0.16	8.8	21.3		2.5	5.0		11.3	26.3	
0.18			33.8			12.5			46.3
0.20	21.3	28.8		3.8	7.5		25.0	36.3	
0.22									
0.24	40.0	48.8		16.3	7.5		56.3	56.3	
0.26									
0.28	45.0			31.3			76.3		

Figure 8 demonstrate how MII occurrence changes by peak sway acceleration (A [g]) and period (P [sec]) in Sway + Roll + Pitch motion.





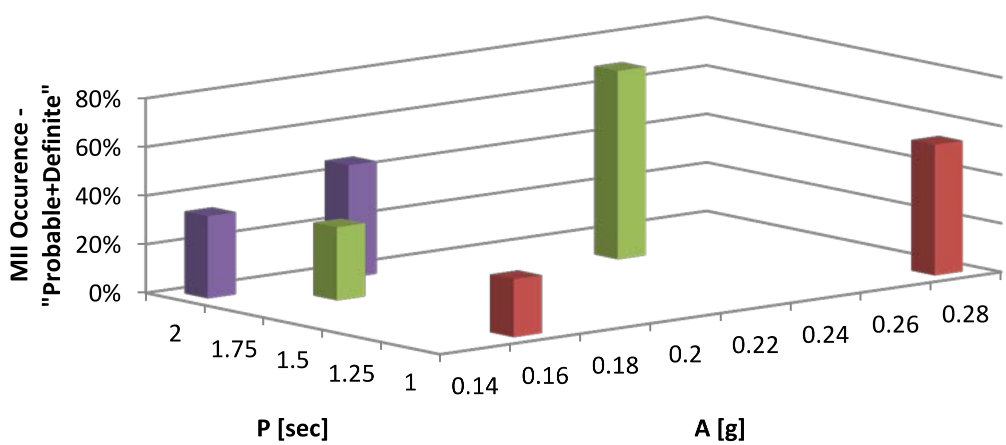


Figure 8. Sway + Roll+ Pitch motion. 3-D figures of MII occurrence ("Probable," "Definite," "Probable + Definite") by peak sway acceleration and period

The percentage-wise MII occurrence in Sway + Roll + Pitch motion is integrated in Table 13.

Table 13. MII occurrence [%] in Sway + Roll + Pitch motion

A [g]	Period [sec]														
	"Probable"					**"Definite"**					**"Probable + Definite"**				
	1	1.25	1.5	1.75	2	1	1.25	1.5	1.75	2	1	1.25	1.5	1.75	2
0.14					25.0					8.8					33.8
0.16	8.8			21.3		15.0			8.8		23.8			30.0	
0.18					27.5					18.8					46.3
0.20															
0.22															
0.24				46.3					31.3					77.5	
0.26															
0.28	26.3					27.5					53.8				

These results show the following points of interest.

- All motion conditions.
    - MII occurrence increases when peak sway acceleration is increased.
    - When "Probable" MIIs increase, "Definite" MIIs also increase.
- Sway-only motion: MII occurrence in sway-only motion increases with increasing sway period (in the range of 1.0 to 2.0 seconds).
- Sway + Roll: Results suggest that the lower sway period (1.25 seconds), combined with roll motion, demonstrates approximately 7.20% more MIIs, compared to the longer sway period (1.50 seconds).
- Sway + Roll + Pitch: MII occurrence increases with increasing sway period (in the range of 1.0 to 2.0 seconds).

D. MODEL DEVELOPMENT

Based on the percentage MIIs results of the previous section, we developed a regression surface. The dependent variable is the percentage MII occurrence derived as a function of the sway motion, which is the stimulus of biodynamic interference in this study. More specifically, the two components of the sinusoidal sway motion are acceleration amplitude (peak acceleration) $\boldsymbol{A}$, and the period $\boldsymbol{P}$ of the sway motion. The model assumes the interaction of two functions: a generalized logistic associated with acceleration amplitude and a Gaussian for period.

The initial form of the generalized logistic function is given in Equation (1):

$$MII(A) = C + \frac{K-C}{\left(1+Qe^{-B(A-M)}\right)^{\frac{1}{n}}}, \tag{1}$$

where:

- A is the sway acceleration amplitude.
- C is the lower asymptote.
- K is the upper asymptote.
- B is the growth rate.
- n is a parameter greater than 0.
- Q and M are parameters.

Given that MII occurrence percentage ranges from 0 to 100, we set C=0 and K=100. Overall, we simplified the previous form to the following:

$$MII_A(A) = \frac{100}{1+e^{-B(A-M)}}, \tag{2}$$

where:

- A is the sway acceleration amplitude.
- B is the growth rate.
- M is a parameter.

The Gaussian function is given by Equation (3):

$$MII_P(P) = e^{-\left(\frac{P-D}{E}\right)^2}, \tag{3}$$

where:

- P is the sway period.
- D and E are parameters.

The model is given by Equation (4):

$$MII(A, P) = 100\frac{1}{1+e^{-B(A-M)}}e^{-\left(\frac{P-D}{E}\right)^2}. \tag{4}$$

Based on this model, we optimized its fit to the data using the *cftool* interface in Matlab (information regarding *cftool* can be found at http://www.mathworks.com/help/curvefit/cftool.html). Table 14 depicts the results of fitting the model to the Sway-only motion condition data.

Table 14. Model attributes in Sway-only motion

Parameter	Probable	Definite	Probable + Definite
B	30.86	32.71	28.84
M	0.1954	0.2769	0.2004
D	2.539	1.954	1.969
E	1.386	0.4598	0.8784

Figures 9 and 10 depict the model prediction for “Probable + Definite” MII occurrence in Sway-only motion.

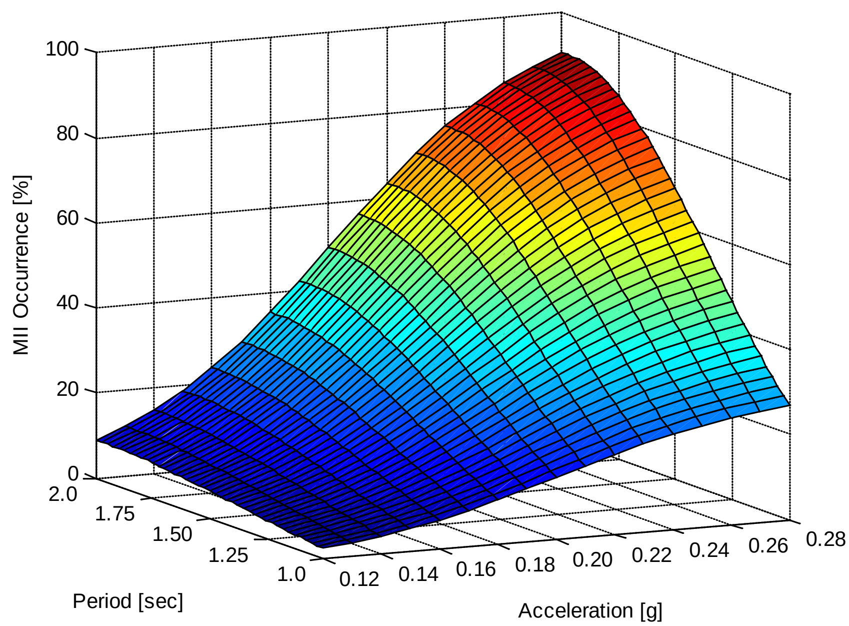


Figure 9. Model prediction of MII occurrence “Probable + Definite” in Sway-only motion

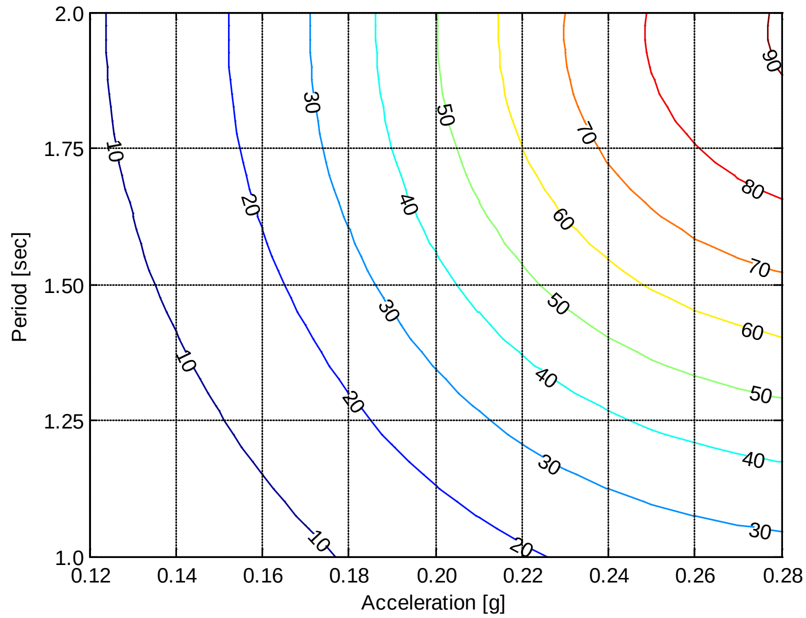


Figure 10. Contour plot of model prediction of MII occurrence “Probable + Definite” in Sway-only motion

Table 15 depicts the results of fitting the model to the Sway and pitch motion condition data.

Table 15. Model attributes in Sway and pitch motion

Parameter	Probable	Definite	Probable + Definite
B	23.05	21.59	22.93
M	0.2098	0.3207	0.2125
D	2.314	0.678	2.147
E	–1.033	8.397	1.495

Figures 11 and 12 depict the model prediction for “Probable + Definite” MII occurrence in Sway + Pitch motion.

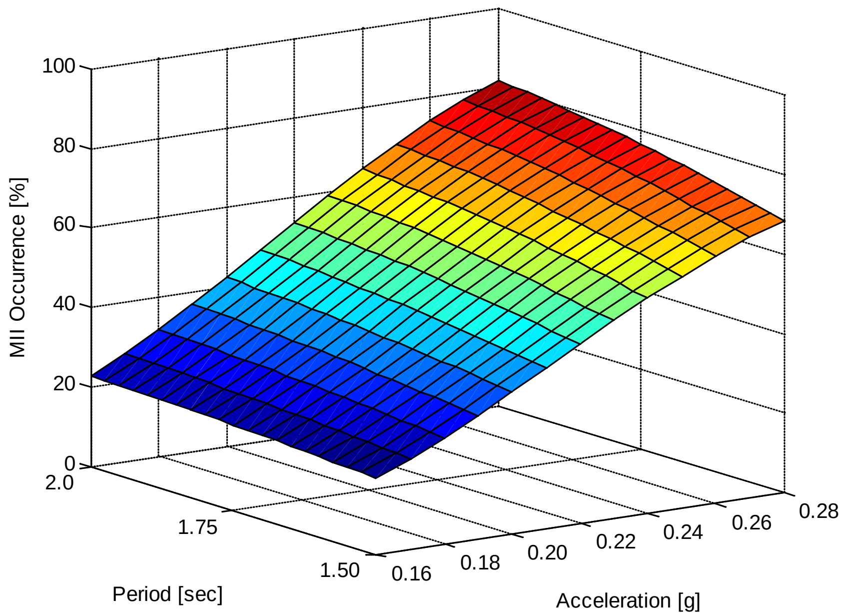


Figure 11. Model prediction of MII occurrence "Probable + Definite" in Sway + Pitch motion

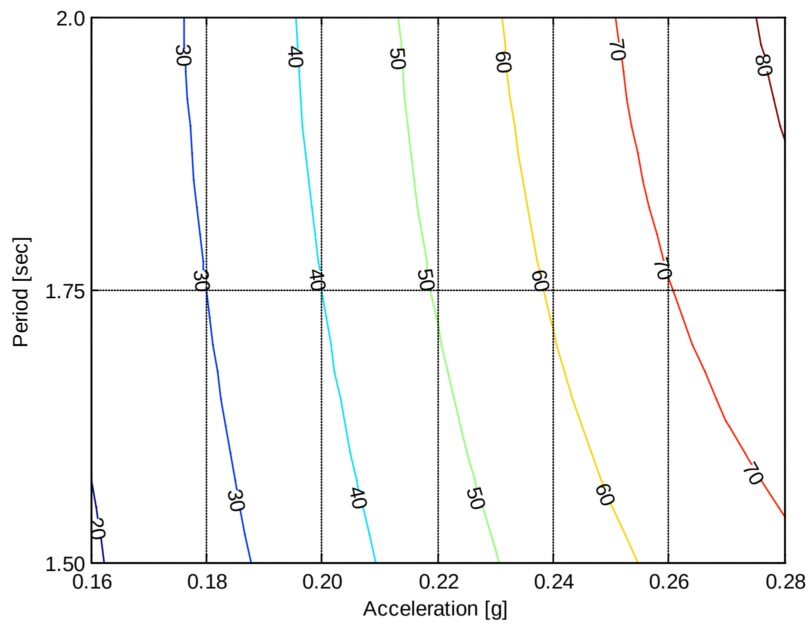


Figure 12. Contour plot of model prediction of MII occurrence "Probable + Definite" in Sway + Pitch motion

Table 16 depicts the results of fitting the model to the Sway and Roll motion condition data.

Table 16. Model attributes in Sway and Roll motion

Parameter	Probable	Definite	Probable + Definite
B	39.99	32.29	28.9
M	0.1611	0.2048	0.1832
D	–1.931	–3.971	0.0244
E	3.16	5.212	2.25

Figures 13 and 14 depict the model prediction for "Probable + Definite" MII occurrence in Sway + Roll motion.

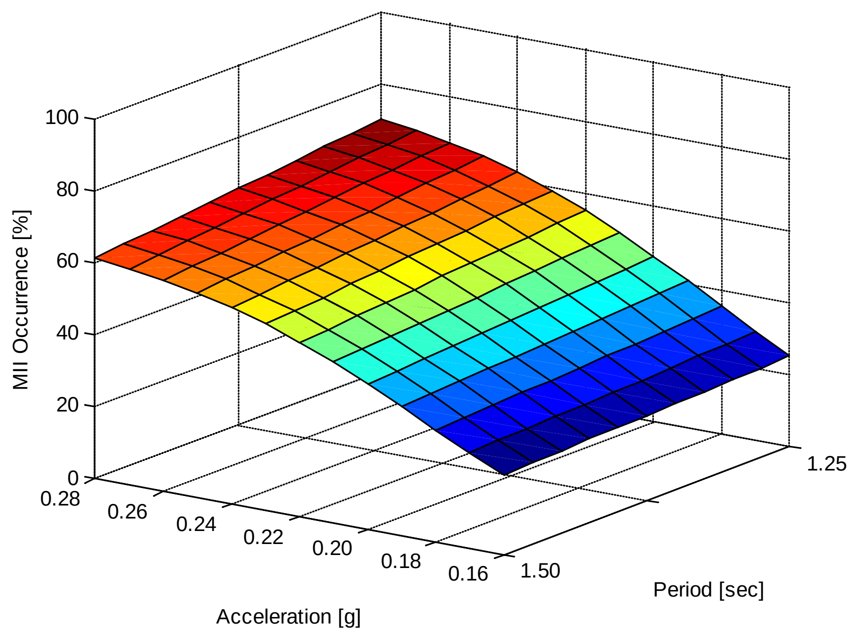


Figure 13. Model prediction of MII occurrence "Probable + Definite" in Sway + Roll motion

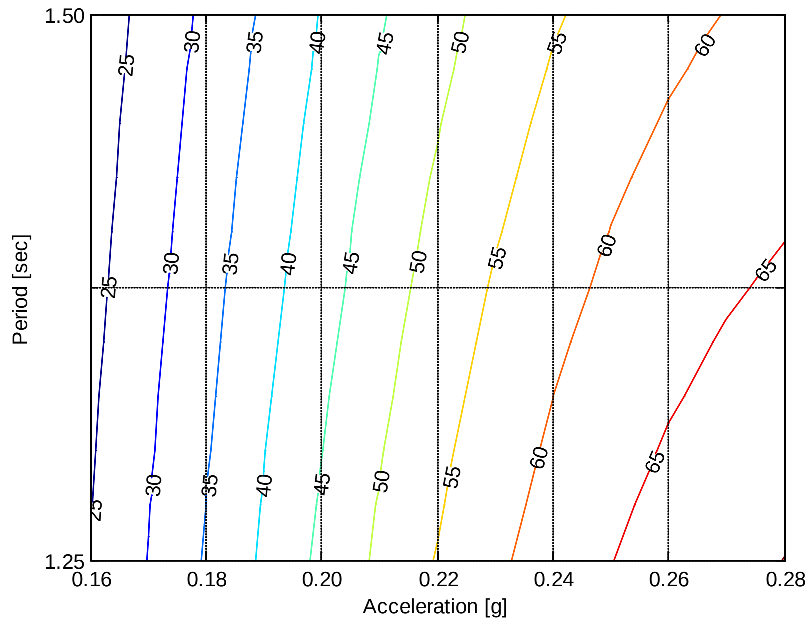


Figure 14. Contour plot of model prediction of MII occurrence "Probable + Definite" in Sway + Roll motion

Table 17 depicts the results of fitting the model to the Sway combined with Roll and Pitch motion condition data.

Table 17. Model attributes in Sway + Roll + Pitch motion

Parameter	**Probable**	**Definite**	**Probable + Definite**
B	14.77	37.95	22.02
M	0.2453	0.1709	0.1834
D	1.945	22.52	2.034
E	1.015	19.42	1.463

Figures 15 and 16 depict the model prediction for "Probable + Definite" MII occurrence in Sway + Roll + Pitch motion.

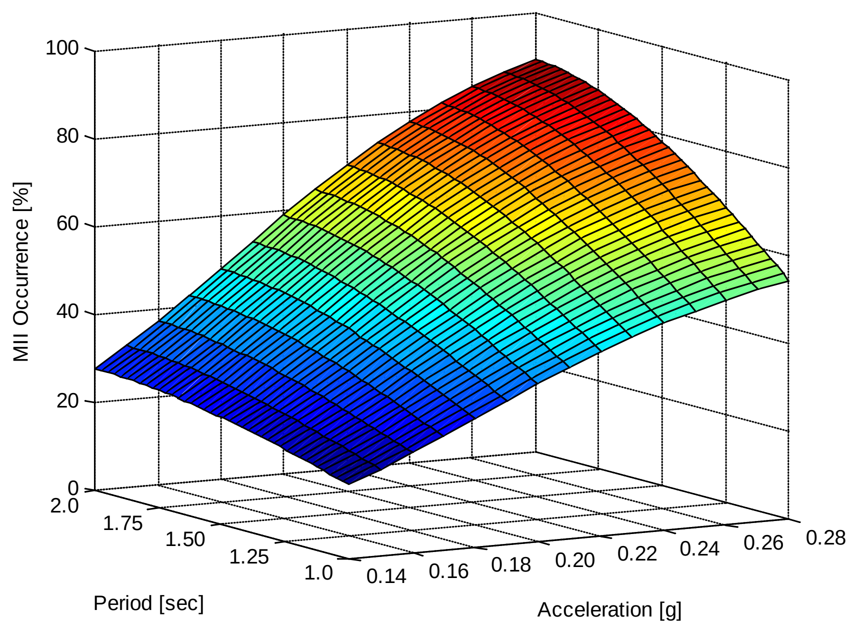


Figure 15. Model prediction of MII occurrence "Probable + Definite" in Sway + Roll + Pitch motion

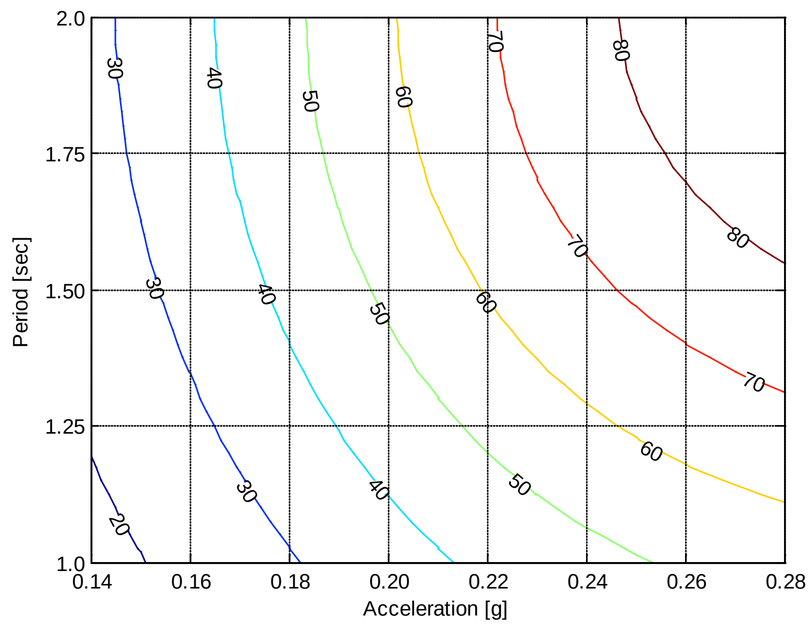


Figure 16. Contour plot of model prediction of MII occurrence "Probable + Definite" in Sway + Roll + Pitch motion

Table 18 shows the differences between observed and predicted MII occurrences in all motion conditions.

Table 18. Differences between predicted and observed MII occurrence

Model	MII	Points	Difference Δ (Predicted-Observed)				
		N	Min	Max	Mean	StDev	Median
Sway	Probable	15	–4.48%	5.11%	0.10%	2.79%	–0.26%
	Definite	15	–3.90%	8.68%	–0.21%	2.88%	0.03%
	Probably + Definite	15	–8.00%	7.00%	–0.07%	3.72%	0.18%
Sway + Pitch	Probable	8	–4.14%	4.20%	0.11%	3.41%	0.32%
	Definite	8	–8.04%	7.16%	–0.47%	4. 40%	–1.11%
	Probably + Definite	8	–14.4%	10.6%	–0.30%	8.48%	0.79%
Sway + Roll	Probable	8	–3.25	2.00	0.03	1.92	0.62
	Definite	8	–1.77	1.33	0.02	1.00	0.29
	Probably + Definite	8	–2.74	2.01	0.04	1.86	0.88
Sway + Roll + Pitch	Probable	6	–7.62	0.54	–1.15	3.17	0.04
	Definite	6	–3.34	3.93	–0.04	2.53	–0.30
	Probably + Definite	6	–5.99	6.01	–0.24	4.09	–0.29

E. SEVERITY OF MIIs: A QUALITATIVE APPROACH

Thus far, we have approached the MIIs from a quantitative perspective; the number of MIIs. It is interesting also to assess the severity of MIIs qualitatively by using the researcher’s evaluation of MII type and group. During data collection, a researcher logged the severity of each MII in three levels, as shown in Table 19.

Table 19. MII groups and types

MII Group	MII Type
Probable	Heel
Definite	Step Both feet, hanging

Results show that lowest MII occurrence was observed in the sway-only condition (M=34.5%), approximately 10% less than the rest of the motion conditions. This phenomenon was merely identified in “Definite” MIIs. In the sway-only motion, the corresponding occurrence was 5.90% and increasing to 10.8% in the Sway + Pitch condition, 18.3% in the Sway + Roll + Pitch, and 20.3% in the Sway + Roll condition. These results also show that motion profiles, including a roll component, induced more “Definite” MIIs compared to motions without roll (With Roll, M=19.3%, Without Roll, MD=8.35%). Lastly, the “Probable” MIIs are more frequent than “Definite” MIIs.

“Probable” MIIs are 58% of the observed MIIs in the Sway + Roll condition and increasing to 84% in the Sway-only conditions. These findings are depicted in Figure 17.

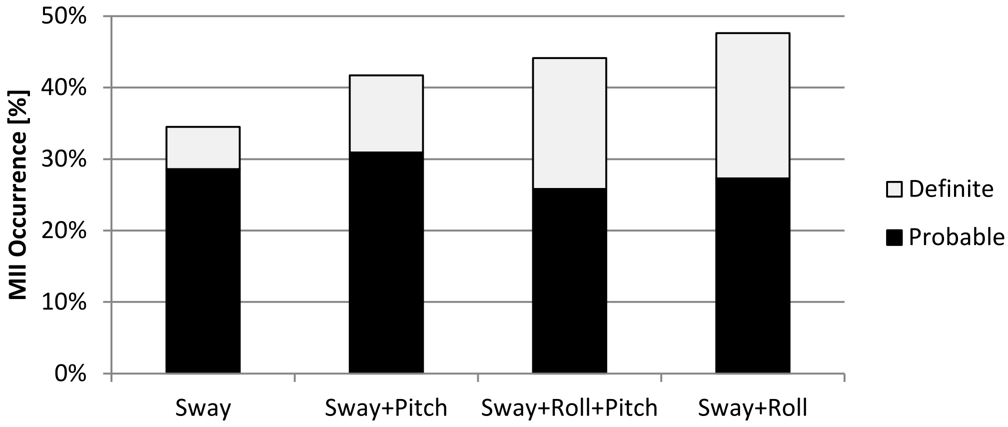


Figure 17. MII occurrence (%) per motion condition

F. THE ASSOCIATION BETWEEN SHARPENED ROMBERG TEST AND MIIS

To assess the association between MIIs in motion and postural equilibrium after the experiment, we used the third administration (post-motion) of the Sharpened Romberg test for the analysis. The mean time was 26.5 seconds (SD=7.65), ranging from 5 to 30 seconds. Four individuals (20%) had a positive sign. No relationship was found between the Sharpened Romberg test sign and MIIs occurrence per Participant (Wilcoxon Rank Sum test, $p>0.40$).

G. SUBJECTIVE RATINGS OF MOTION SEVERITY

After each sway trial, Participants rated the intensity of motion regardless of an MII occurrence. Analysis identified an association between self-reported motion intensity and type of motion condition, Likelihood Ratio test, X2(12, N = 2368) = 29.5, $p < 0.001$. These results are demonstrated in Figure 18.

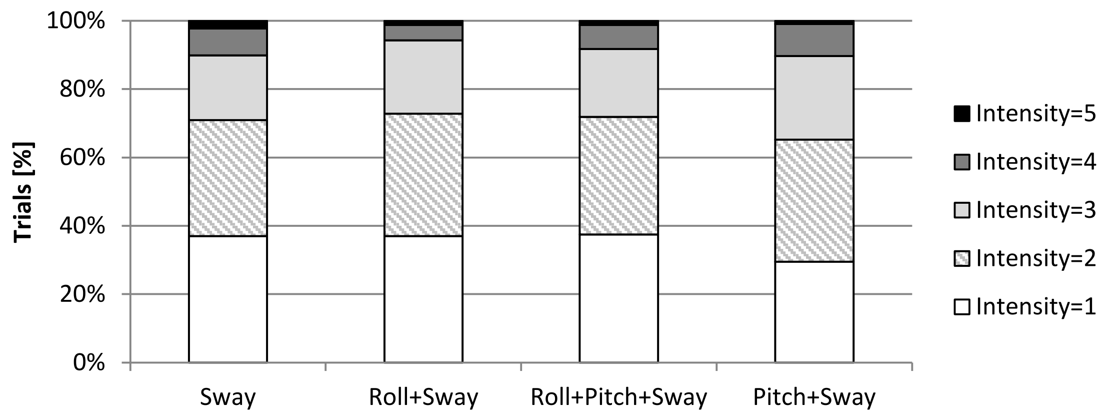


Figure 18. Motion intensity per motion condition

Examination of the cell frequencies showed the subjectively evaluated worst motion condition is the sway combined with pitch. This finding is in contrast to the result reported earlier that the maximum MII occurrence was observed in the Sway + Roll condition.

H. COMPARISON WITH MII MODEL

The average stance width of our Participants was 14.1 inches (SD=1.97, MD=14.2). The average stance width for males (n=15) was 14.9 inches (SD=1.75, MD=15.0, minimum=11.8, maximum=19.7), and for the females (n=5) was 11.9 inches (SD=0.757, MD=11.8, minimum=11.0, maximum=13.0). The convenient stance width was associated with height (stature) (one-way ANOVA, $F(1,18)=11.5$, $p=0.003$).

The center of gravity (CoG) was not assessed experimentally. Instead, our approach was based on the information provided in existing literature. The CoG of a male human is approximately 57% of his height (stature), whereas for a female, the CoG is 55% of her height (McGinnis, 2013, p. 149). One Participant's CoG data was missing and estimated by a regression equation. Based on these CoG values, we calculated the corresponding theoretical tipping coefficients for each Participant, as shown in 0 in Appendix D. The mean theoretical tipping coefficient was 0.175 (SD=0.020, MD=0.177, minimum=0.146, maximum=0.237).

Next, we compared the observed and the predicted incidence of MIIs. Given that the total number of MII trials in the experiment is 608, we observed 36 MIIs, whereas the model predicts 604 (almost 17 times more). Therefore, it is concluded that the rigid body model considerably overpredicts MII occurrence. These results are shown in Table 20.

Table 20. Observed MIIs versus predicted by the Rigid Body Model in sway-only motion

		Rigid Model Predictions		
		Yes	No	Total
Experimental	Yes	36	0	36
Observations	No	568	4	572
	Total	604	4	608

The corresponding global tipping coefficient was approximately 0.45.

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IV. DISCUSSION

This study assesses lateral tipping MIIs of standing persons in a simulated motion environment representing dry deck conditions. The major finding of this experiment was that the occurrence of lateral MIIs is not only associated with sway acceleration amplitude, but with motion frequency characteristics and motion complexity.

In congruence with previous MII research (e.g., Baker & Mansfield, 2010; Brown et al., 2001), this study shows that MII occurrence increases by increasing peak sway acceleration consistently in all motion conditions.

The effect of frequency on MII occurrence, however, is not as clear as that of acceleration. In the present study, MII occurrence increases by increasing period in sway-only and sway + roll + pitch motion, but this finding is less evident in the sway + pitch motion condition. The trend, however, seems to be reversed when sway is combined with roll; lower sway period (1.25 seconds) demonstrated approximately 7% more MIIs compared to the higher sway period (1.5 seconds). These findings are integrated in Table 21 (e.g., in the sway-only condition increased sway frequency leads to less MIIs, whereas more acceleration leads to more MIIs).

Table 21. Tipping MII occurrence by sway motion attribute (peak acceleration and frequency)

Motion Condition	**Sway Motion Attributes**	
	Peak Acceleration	**Frequency**
Sway only	↗	↘
Sway + Roll	↗	↗
Sway + Pitch	↗	↘
Sway + Roll + Pitch	↗	↘

These results suggest that, within the motion envelope we investigated, the combination of sway motion with roll or pitch had a differential effect on the MII occurrence. Given that the legacy, rigid body MII model does not explicitly incorporate frequency, this finding contributes to our knowledge about MII occurrence.

Based on existing literature and the findings in this study, we postulate that the association between lateral MII occurrence and motion attributes is influenced by overall motion complexity and frequency characteristics. Earlier research identified that the effects of motion on postural control are frequency-dependent (Bles et al., 2002; Crossland et al., 1994; Crossland & Lloyd, 1993; Nawayseh & Griffin, 2006; Sari & Griffin, 2009) and that the effect of frequency on MIIs depends on the direction of the human body compared to a ship's axes (Crossland et al., 1994; Crossland & Lloyd, 1993). These studies, however, provided contradicting evidence regarding the association between the motion frequency and the severity of biodynamic problems.

We believe that the explanation lies in how the human postural equilibrium system perceives induced-motion perturbations and compensates for them. In this context, compensation includes both the biomechanical (Bortolami, DiZio, Rabin, & Lackner, 2003) and the cognitive component. In a study conducted by Buchanan and Horak (1999), the researchers examined the frequency characteristics of human postural coordination with standing Participants during sinusoidal translations (12 cm peak to peak) in the anterior-posterior direction at six different frequencies. They concluded that human sensory and biomechanical constraints limit postural coordination patterns as a function of translation frequency. Center of mass motion amplitude decreased with increasing translation frequency, whereas the center of pressure amplitude increased with increasing translation frequency. Research also has identified the complex, nonlinear, coordination patterns between stimulus movement and postural response (Dijkstra, Schöner, Giese, & Gielen, 1994). The cognitive component includes the perceptual-cognitive cycle of identifying induced motion profiles and predicting future perturbations (e.g., Horak & Nashner, 1986).

Our findings are consistent with the complex dynamics underlying human posture control and, hence, the development of an MII. Excluding the time component, it seems that MII investigations should focus not only on the motion stimulus attributes (axis, acceleration, and frequency), but also on how the human perceives and reacts to motion.

Overall, our data suggest two notable results. First, complex multidirectional motions create more tipping MIIs than simple, unidirectional motion; probably because complex motions are less predictable by the human (Crossland, 2005; Horak & Nashner, 1986). Second, for a standing person facing fore/aft, the roll component significantly deteriorates standing balance. Our results show that motions including a roll component double the occurrence of definite MIIs compared to motions without roll, from 8.35% to 19.3%.

Based on our findings, we developed a mathematical model of MII occurrence as a function of the amplitude and period of motion stimulus acceleration. The model assumes an additive combination of two functions: a generalized logistic associated with the amplitude of acceleration and a Gaussian for period. The developed model approximated the observed MIIs with good results (< +/– 9% difference).

In conjunction with earlier research, these results verify that the rigid body model of Graham (1990) considerably overpredicts MII occurrence (McCauley, Pierce, & Matsangas, 2007). The estimated global tipping coefficient is almost doubled, compared to the corresponding values found in experiments where Participants are involved with a task (Crossland et al., 2007; Crossland & Lloyd, 1993). Therefore, our Participants seemed to be "insensitive" to the lateral motion perturbations. This result is reasonable given that in this study, Participants were free to focus in maintaining their posture without being involved in other tasks.

Second, the observed occurrence of MIIs in this study should be regarded as a best-case scenario because our Participants had their eyes open and had a stable visual reference, which is known to be associated with decreased MIIs (Dobie, May, & Flanagan, 2003).

In this study, we introduced the "probable" MII; it is a novel term referring to an event where the individual temporarily loses balance slightly, but to an extent that is obvious to an external observer. An example is a slight elevation of the heel, but not severe enough to be counted as a clear tipping MII because the individual does not displace their foot.

The "probable MII" fills the gap between the theoretical definition of an MII, and a human perceiving an MII. In existing research, an MII is defined as a loss-of-balance incidence due to tipping or sliding (Baitis et al., 1984; Graham, 1990). The MII is considered to occur whenever the forces acting on the person (acting as a rigid body) cause one foot to lift off the ground (Graham et al., 1992). Useful as it may be, this definition overlooks how the human reacts to balance perturbations by changing their center of mass and adjusting body posture to compensate for motion. Hence, loss of balance is not a binary phenomenon. It may include a partial loss of balance, where the individual must stop their task for a short period of time. In this grey area of balance perturbations, portions of both feet may continue to touch the ground and, therefore, tipping does not occur. The human, however, adjusts their posture by moving their hands, bending, or lowering their center of gravity. In our experiment, the Participants were instructed to keep their hands relaxed at their side. In "probable" MIIs they tended to move one of their heels or to move their hands outward to readjust their center of gravity. From the conventional MII perspective, this posture change is not an MII. It may be an MII, however, if we consider a human performing a manual task that has to stop, even temporarily, because of motion.

From a human performance perspective, the investigation of the "probable" MIIs may be of value because they are more common than the "definite" MIIs (depending on the motion profile, this difference ranged from 16% to 67%).

V. RECOMMENDATIONS FOR FUTURE RESEARCH

The results of this study support the following recommendations:

- Although the number of Participants used in this study is comparable to existing MII research (Crossland & Lloyd, 1993), future efforts should include a larger sample to enable analysis of demographic attributes, such as ship motion experience and MII occurrence.
- Although we used the Sharpened Romberg test, future efforts should include more elaborate and validated tools to assess human postural stability (e.g., Chaudhry et al., 2005).
- Heave oscillation undoubtedly affects friction between the Participants' feet and the deck surface. Heave, combined with complex multidimensional motion, needs to be investigated to enable a more comprehensive model of MIIs aboard ship.
- Assess the association between MII occurrence and displacement, compared with the support base dimensions.
- Simulator platforms with a larger envelope of sway displacement are needed to address the motion envelope of interest.
- Integrate the functional stability region (Holbein & Redfern, 1997; McDermott et al., 2005) with the rigid body model.

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APPENDIX A. PRE- AND POSTTEST QUESTIONNAIRES

Pretest Questionnaire

Screening

Instructions: *Please answer ALL questions as accurately as possible*

1) Please identify whether you have been diagnosed with one or more of the following vestibular related issues (Check one ☑ per row):

a) Benign positional vertigo	☐ Yes	☐ No
b) Meniere's syndrome	☐ Yes	☐ No
c) Viral neurolabyrinthitis	☐ Yes	☐ No
d) Labyrinthine defects	☐ Yes	☐ No
e) Labyrinthectomies	☐ Yes	☐ No
f) Vestibular neuronitis	☐ Yes	☐ No
g) Vertigo (peripheral or of central origin)	☐ Yes	☐ No
h) Other disorders of vestibular function	☐ Yes	☐ No

2) Please identify whether you have been diagnosed with one or more of the following disorders or health issues (Check one ☑ per row):

a) Migraines	☐ Yes	☐ No
b) Gastrointestinal disorders	☐ Yes	☐ No
c) Cardiovascular disorders	☐ Yes	☐ No
d) Photic seizures	☐ Yes	☐ No
e) Claustrophobia	☐ Yes	☐ No

f) Other. Please indicate: ____________________

3) Have you ever had an ear illness or injury, which was accompanied by dizziness and/or nausea? (Check one ☑) ☐ Yes ☐ No

a) If "YES", please specify: ____________________

4) Have you ever had back, leg, or ankle injuries? (Check one ☑) ☐ Yes ☐ No

5) Are you in your usual state of fitness? (☑ one answer only) ☐ Yes ☐ No

a) If "NO," please indicate the reason: ____________________

6) Have you been ill in the past week? (☑ one answer only) ☐ Yes ☐ No

a) If "YES", please indicate the nature of the illness (flu, cold, etc ____________________

b) If "YES", please indicate the severity of the illness (☒ one answer only):

- ☐ Very Mild
- ☐ Moderate
- ☐ Very Severe

c) If "YES", please indicate the length of illness: _____ (Hours or Days)

d) If "YES", please indicate the major symptoms (list):the illness (flu, cold, etc ______________________

e) If "YES", please indicate whether you are you fully recovered? (☒ one answer only) ☐ Yes ☐ No

6) Have you used any medication (either over-the-counter or prescription during the last 24 hours? (☒ one answer only) ☐ Yes ☐ No

a) If "YES", please indicate all medication you have used in the past 24 hours. (If possible, specify type, dosage, and time taken):

7) Have you consumed any alcohol (beer, wine, hard liquor, etc) during the last 24 hours? (☒ one answer only) ☐ Yes ☐ No

8) Did you have breakfast this morning? (☒ one answer only) ☐ Yes ☐ No

9) How many caffeinated drinks did you consume this morning? (coffee, tea, caffeinated beverages, etc) (☒ one answer only)

- ☐ None
- ☐ 1
- ☐ 2
- ☐ More

10) How many hours of <u>actual sleep</u> did you get last night? (This may be different than the number of hours you spend in bed) (Please type a number) ____________hours

11) Was this last night sleep amount sufficient? (☒ one answer only) ☐ Yes ☐ No

12) Please list any other comments regarding your present physical state, which might affect your performance on our test:

General

Instructions: *Please answer ALL questions as accurately as possible.*

13) What is your service? (check one)

Navy	☐	Army	☐
Air Force	☐	USCG	☐
Other	☐	Civilian	☐

14) What is your shoe size? (Men's or Women's?) ______________

15) What is your age?: (Years) ______________

16) What is your gender? (Check one ☒): ☐ Male ☐ Female

17) What is your height (in feet & inches): ______ ft. ______ in.

18) What is your weight? (pounds):
19) Total time in service, in years
20) Total sea time or flight time in years: ____________

21) Using the left scale below, rate the degree you feel the statements at the <u>right now</u>. Please put a number from 1 –9 in each of the 16 items.

Rate Scale	I felt:	
Not at all — **Severely** 1 2 3 4 5 6 7 8 9	1. Sick to my stomach	________
	2. Faint-like	________
	3. Annoyed/ irritated	________
	4. Sweaty	________
	5. Queasy	________
	6. Lightheaded	________
	7. Drowsy	________
	8. Clammy/ cold sweat	________
	9. Disoriented	________
	10. Tired/ fatigued	________
	11. Nauseated	________
	12. Hot/ warm	________
	13. Dizzy	________
	14. Like I was spinning	________
	15. As if I may vomit	________
	16. Uneasy	________

Posttest Questionnaire

1. Please provide an overall rate of the severity of Motion Induced Interruptions during your data collection session.

   [Motion Induced Interruptions are all kind of interruptions in your duty caused by ship's motion. If standing, an MII could be: sliding, losing your stance, not being able to walk, having to get hold of anything firm so as to continue conducting your task. If seated, an MII could be: hold your chair so as not to slide, hold your console so as to continue watching the scope, unusual difficulty in using your keyboard or other controls due to ship's motion. In general, whenever the ship's motion is making you stop what you have been doing, even for a short amount of time, it is assumed to be an MII].

Not at all | Mild | Severe

-3 | -2 | -1 | 0 | 1 | 2 | 3

2. Using the left scale below, rate the degree you experienced the statements at the right during your data collection session. Please put a number from 1 –9 in each of the 16 items.

Rate Scale	I felt:	
	1. Sick to my stomach	________
	2. Faint-like	________
	3. Annoyed/ Irritated	________
	4. Sweaty	________
	5. Queasy	________
	6. Lightheaded	________
	7. Drowsy	________
	8. Clammy/ cold sweat	________
	9. Disoriented	________
Not at all **Severely**	10. Tired/ fatigued	________
	11. Nauseated	________
1 2 3 4 5 6 7 8 9	12. Hot/ warm	________
	13. Dizzy	________
	14. Like I was spinning	________
	15. As if I may vomit	________
	16. Uneasy	________

APPENDIX B. PARTICIPANTS AND COLLECTED DATA

Participant ID	Motion Profile	Screening and Pretest Q.	Midtest Q.	Posttest Q.	Motion Profile/Noldus Video	Researchers' Data
3001	1-2-3-4	√	√	√	√	√
3102 *	1-2-3-4	√	√	√	√	√
0103	1-2-3-4	√	√	√	√	√
0501	1-2-3-4	√	√	√	√	√
0603	1-2-3-4	√	√	√	√	√
0802	1-2-3-4	√	√	√	√	√
2902 *	1-2-3-4	√	√	√	√ (1-NA-NA-NA)	
3002	2-3-4-1	√	√	√	√	√
3103	2-3-4-1	√	√	√	√	√
0201	2-3-4-1	√	√	√	√	√
0502	2-3-4-1	√	√	√	√	√
0701	2-3-4-1	√	√	√	√	√
3003	3-4-1-2	√	√	√	√	√
0101	3-4-1-2	√	√	√	√	√
0601	3-4-1-2	√	√	√	√	√
0702	3-4-1-2	√	√	√	√	√
0202	3-4-1-2	√	√	√	√ (3-4-NA-2)	√
3101	4-1-2-3	√	√	√	√	√
0102	4-1-2-3	√	√	√	√	√
0203	4-1-2-3	√	√	√	√	√
0602	4-1-2-3	√	√	√	√	√
0801	4-1-2-3	√	√	√	√	√

"√" means that the corresponding data exist
"*" means that the corresponding data were not included in the analysis
Motion Conditions: "1"=Sway, "2"=Pitch+Sway, "3"=Roll+Sway, "4"=Roll+Pitch+Sway
"NA" = Not available data

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APPENDIX C. MOTION CHARACTERISTICS FOR EACH TRIAL

A. SWAY-ONLY MOTION SESSION

Table 22 demonstrates in detail the motion characteristics in each trial. Trials 12 and 28 are the ones affected by motion platform displacement limit. "Modifier" refers to the iteration of acceleration-period combination (e.g., the 16 trials with the same acceleration-period combination were repeated twice).

Table 22. Attributes of Sway Trials

Trial Number	Modifier	Acceleration (peak g)	Period (sec)	Direction
T1	1	0.16	1.00	L
T2	1	0.20	1.00	R
T3	1	0.24	1.00	R
T4	1	0.28	1.00	L
T5	1	0.16	1.50	R
T6	1	0.20	1.50	L
T7	1	0.24	1.50	L
T8	1	0.28	1.50	R
T9	1	0.16	1.75	L
T10	1	0.20	1.75	R
T11	1	0.24	1.75	R
T12	1	0.28	1.50	L
T13	1	0.12	2.00	R
T14	1	0.14	2.00	L
T15	1	0.16	2.00	L
T16	1	0.18	2.00	R
T1	2	0.16	1.00	R
T2	2	0.20	1.00	L
T3	2	0.24	1.00	L
T4	2	0.28	1.00	R
T5	2	0.16	1.50	L
T6	2	0.20	1.50	R
T7	2	0.24	1.50	R
T8	2	0.28	1.50	L
T9	2	0.16	1.75	R
T10	2	0.20	1.75	L
T11	2	0.24	1.75	L
T12	2	0.28	1.50	R
T13	2	0.12	2.00	L
T14	2	0.14	2.00	R
T15	2	0.16	2.00	R
T16	2	0.18	2.00	L

Note that the Direction and Phase conditions are not a full-factorial design, but were intended to make the time of initiation and direction of the sway impulse unpredictable by the Participant.

B. PITCH AND SWAY MOTION SESSION

Table 23 demonstrates in detail the motion characteristics in each trial. Trials 8, 16, 24, and 32 are the ones affected by the motion platform displacement limit.

Table 23. Attributes of Sway + Pitch trials

Trial Number	Modifier	Sway Acceleration (peak g)	Sway Period (sec)	Sway Direction
T1	1	0.24	1.50	L
T2	1	0.28	1.50	R
T3	1	0.24	1.73	L
T4	1	0.20	1.50	R
T5	1	0.24	1.73	R
T6	1	0.16	1.75	L
T7	1	0.28	1.50	L
T8	1	0.28	1.50	L
T1	2	0.20	1.50	R
T2	2	0.18	2.00	L
T3	2	0.24	1.50	R
T4	2	0.16	1.50	L
T5	2	0.24	1.50	R
T6	2	0.16	1.75	L
T7	2	0.20	1.50	L
T8	2	0.20	1.50	R
T1	3	0.28	1.50	L
T2	3	0.20	1.75	L
T3	3	0.20	1.75	R
T4	3	0.16	1.50	L
T5	3	0.18	2.00	R
T6	3	0.16	1.75	R
T7	3	0.16	1.50	L
T8	3	0.20	1.75	R
T1	4	0.18	2.00	L
T2	4	0.20	1.75	R
T3	4	0.24	1.73	R
T4	4	0.16	1.75	L
T5	4	0.24	1.73	R
T6	4	0.18	2.00	L
T7	4	0.16	1.5	R
T8	4	0.24	1.5	R

C. ROLL AND SWAY MOTION SESSION

Table 24 demonstrates, in detail, the motion characteristics in each trial.

Table 24. Attributes of Sway + Roll trials

Trial Number	Modifier	Sway Acceleration (peak g)	Sway Period (sec)	Sway Direction
T1	1	0.24	1.25	L
T2	1	0.28	1.25	R
T3	1	0.24	1.50	L
T4	1	0.20	1.25	R
T5	1	0.24	1.50	R
T6	1	0.16	1.50	L
T7	1	0.28	1.25	L
T8	1	0.28	1.25	L
T1	2	0.20	1.25	R
T2	2	0.28	1.50	L
T3	2	0.24	1.25	R
T4	2	0.16	1.25	L
T5	2	0.24	1.25	R
T6	2	0.16	1.50	L
T7	2	0.20	1.25	L
T8	2	0.20	1.25	R
T1	3	0.28	1.25	L
T2	3	0.20	1.50	L
T3	3	0.20	1.50	R
T4	3	0.16	1.25	L
T5	3	0.28	1.50	R
T6	3	0.16	1.50	R
T7	3	0.16	1.25	L
T8	3	0.20	1.50	R
T1	4	0.28	1.50	L
T2	4	0.20	1.50	R
T3	4	0.24	1.50	R
T4	4	0.16	1.50	L
T5	4	0.24	1.50	R
T6	4	0.28	1.50	L
T7	4	0.16	1.25	R
T8	4	0.24	1.25	R

D. PITCH, ROLL, AND SWAY MOTION SESSION

Table 25 demonstrates, in detail, the motion characteristics in each trial.

Table 25. Attributes of Sway + Pitch + Roll trials

Trial Number	Modifier	Sway Acceleration (peak g)	Sway Period (sec)	Sway Direction
T1	1	0.16	1.75	R
T2	1	0.24	1.75	R
T3	1	0.18	2.00	R
T4	1	0.28	1.00	L
T5	1	0.14	2.00	R
T6	1	0.14	2.00	R
T1	2	0.24	1.75	L
T2	2	0.24	1.75	L
T3	2	0.28	1.00	L
T4	2	0.16	1.00	L
T5	2	0.16	1.75	L
T6	2	0.16	1.00	R
T1	3	0.16	1.75	L
T2	3	0.14	2.00	R
T3	3	0.28	1.00	R
T4	3	0.28	1.00	L
T5	3	0.24	1.75	L
T6	3	0.18	2.00	L
T1	4	0.18	2.00	R
T2	4	0.16	1.00	R
T3	4	0.16	1.75	L
T4	4	0.14	2.00	L
T5	4	0.16	1.00	R
T6	4	0.18	2.00	R

APPENDIX D. DEMOGRAPHICS AND TIPPING COEFFICIENT

Table 26. Participants' height, weight, shoe size, and theoretical tipping coefficient

Participant ID	Gender	Height (in)	Weight (lbs)	Shoe Size	Convenient Stance Width (in)	Theoretical Tipping Coefficient
3001	M	72.25	209.4	11	15.0	0.182
3002	M	76	251	13	14.6	0.168
3003	M	67.75	224.6	10.5	13.8	0.178
3101	F	67.5	132.8	8	11.4	0.154
3103	M	71	198.8	9.5	14.2	0.175
0101	M	67.75	132.4	9	14.6	0.189
0102	M	69	157.4	10	12.6	0.160
0103	M	73	262.2	12.5-13	19.7	0.237
0201	M	72	218.4	10	15.0	0.182
0202	F	65	135	7	11.5	0.160
0203	F	65.75	164.8	8.5	12.2	0.169
0501	M	73.25	266.4	11	15.0	0.179
0502	M	71.75	203.6	11	15.4	0.188
0601	F	67.75	169	8	11.0	0.148
0602	M	70.75	156.4	9.5	11.8	0.146
0603	M	72.5	176.8	10.5	15.0	0.181
0701	M	70	234.6	10.5	14.2	0.178
0702	M	72	174.2	10	16.1	0.197
0801	F	72.5	223	10	13.0	0.163
0802	F	68	171	10	11.8	0.158

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APPENDIX E. PRELIMINARY FINDINGS AND INSIGHTS

We began the preliminary trials using one of the researchers as the "Participant" to determine whether the motion platform was behaving correctly in response to the programmed motion parameters. We started with the simplest linear motion, from point A to point B. The lowest level of acceleration (0.08 g) was used, and the shortest period of acceleration (0.5 seconds). The sway acceleration was very easily tolerated, with no MIIs. The acceleration level was incremented on successive trials and continued to be benign, even as the acceleration level increased beyond the 0.16 g limit identified in Table 1 as "Extremely Hazardous." That result was surprising and unexpected.

In the preliminary testing, we also varied the time of application. The observed preliminary results were that, for a given level of acceleration, longer periods of acceleration (longer than 0.5 seconds, up to approximately 2.0 seconds) were more likely to induce an MII than shorter periods of acceleration. At the 0.5 seconds of duration (the shortest), we did not observe an MII until reaching 0.50 g. That is an acceleration value more than three times (3.12) greater than the maximum limit suggested by Baitis et al. (1984).

The next step in the preliminary testing was to change the basic nature of the sway motion, from A-to-B to a "round trip" motion (A-to-B-to-A). This type of motion was equivalent to one cycle of a sine wave. One member of the research team has considerable time at sea and, in his opinion, this two-way motion cycle is much more similar to ship motion than a single, linear displacement. Further trials of the two-way sway motion were observed and appeared to result in a higher probability of MII at lower levels of acceleration compared to the one-way sway motion. Based on those observations, we chose to implement the two-way sway motion for all subsequent data collection; in part, because the displacement limits were an obstacle for fully exploring the effects of higher sway accelerations.

We believe that two preexperiment findings may be of interest:

- The level of sway acceleration needed to induce an MII was considerably greater than the predictions of Baitis et al. (1984) shown in Figure 1 of this report.

- A two-way cycle of motion may be more representative of ship motion and may be more likely to result in an MII, compared to a one-way linear acceleration.

LIST OF REFERENCES

Applebee, T. R., McNamara, T. M., & Baitis, A. E. (1980). *Investigation into the seakeeping characteristics of the US Coast Guard 140-ft WTGB class cutters: Sea trial aboard the USCGC MOBILE BAY*. Bethesda, MD: Naval Ship Research and Development Center (NSDRC).

Baitis, A. E., Applebee, T. R., & McNamara, T. M. (1984). Human factors considerations applied to operations on the FFG-8 and LAMPS MK-III. *Naval Engineers Journal*, *96*(3), 191–199.

Baitis, A. E., Bales, S. L., McCreight, W. R., & Meyers, W. G. (1976). *Prediction of extreme ammunition cargo forces at sea* (S. Performance, Trans.). Bethesda, MD: Naval Ship Research and Development Center.

Baitis, A. E., Woolaver, D. A., & Beck, T. A. (1983). Rudder roll stabilisation for Coast Guard cutters and frigates. *Naval Engineers Journal*, *95*(3), 267–282.

Baker, W. D. R., & Mansfield, N. J. (2010). Effects of horizontal whole-body vibration and standing posture on activity interference. *Ergonomics*, *53*(3), 365–374.

Bles, W., Nooy, S., & Boer, L. C. (2002). Influence of ship listing and ship motion on walking speed. In M. Schreckenberg & S. D. Sharma (Eds.), *Proceedings of Conference on Pedestrian and Evacuation Dynamics* (pp. 437–452). Berlin, Germany: Springer.

Bortolami, S. B., DiZio, P., Rabin, E., & Lackner, J. R. (2003). Analysis of human postural responses to recoverable falls. *Experimental Brain Research*, *151*, 387–404.

Brown, L. A., Jensen, J. L., Korff, T., & Woollacott, M. H. (2001). The translating platform paradigm: Perturbation displacement waveform alters the postural response. *Gait and Posture*, *14*, 256–263.

Buchanan, J. J., & Horak, F. B. (1999). Emergence of postural patterns as a function of vision and translation frequency. *Journal of Neurophysiology*, *81*(5), 2325–2339.

Chaudhry, H., Findley, T., Quigley, K. S., Ji, Z., Maney, M., Sims, T., . . . Fould, R. (2005). Postural stability index is a more valid measure of stability than equilibrium score. *Journal of Rehabilitation Research and Development*, *42*(4), 547–556.

Colwell, J. L. (1989). *Human factors in the naval environment: A review of the motion sickness and biodynamic problems*. Dartmouth, Nova Scotia: Canadian National Defence R&D Branch.

Crossland, P. (2005, 20-22 August). *The influence of ship motion induced lateral acceleration on walking speed.* Paper presented at the 2nd International Conference on Pedestrian and Evacuation Dynamics 2003, Greenwich, UK.

Crossland, P., & Lloyd, A. R. J. M. (1993). *Experiments to quantify the effects of ship motions on crew task performance – Phase I, motion induced interruptions and motion induced fatigue*. Farnborough, UK: Defence Research Agency.

Crossland, P., & Rich, K. J. N. C. (1998). *Validating a model of the effects of ship motion on postural stability.* Paper presented at the International Conference on Environmental Ergonomics (ICEE), San Diego, CA.

Crossland, P., Colwell, J. L., Baitis, A. E., Holcombe, F. D., & Strong, R. (1994). *Quantifying human performance degradation in a ship motion environment: Experiments at the US Naval Biodynamics Laboratory. International Seminar on Comfort on Board and Operability Evaluation of High-Speed Marine Vehicles*, Genoa, Italy.

Crossland, P., Evans, M. J., Grist, D., Lowten, M., Jones, H., & Bridger, R. S. (2007). Motion-induced interruptions aboard ship: Model development and application to ship design. *Occupational Ergonomics*, *7*(3), 183–199.

Dijkstra, T. M. H., Schöner, G., Giese, M. A., & Gielen, C. C. A. M. (1994). Frequency dependence of the action-perception cycle for postural control in a moving visual environment: Relative phase dynamics. *Biological Cybernetics*, *71*(6), 489–501.

Dobie, T. G., May, J., & Flanagan, M. B. (2003). The influence of visual reference on stance and walking on a moving surface. *Aviation Space and Environmental Medicine*, *74*(8), 838–845.

Gianaros, P. J., Muth, E. R., Mordkoff, J. T., Levine, M. E., & Stern, R. M. (2001). A questionnaire for the assessment of the multiple dimensions of motion sickness. *Aviation Space and Environmental Medicine*, *72*(2), 115–119.

Graham, R. (1990). Motion-induced interruptions as ship operability criteria. *Naval Engineers Journal*, *102*(2), 65–71.

Graham, R., Baitis, A. E., & Meyers, W. G. (1991). *A frequency domain method for estimating the incidence and severity of sliding*. Bethesda, MD: David Taylor Research Center (DTRC).

Graham, R., Baitis, A. E., & Meyers, W. G. (1992). On the development of seakeeping criteria. *Naval Engineers Journal, 104*(3), 259–275.

Greve, J., Cuğ, M., Dülgeroğlu, D., Brech, G. C., & Alonso, A. C. (2013). Relationship between anthropometric factors, gender, and balance under unstable conditions in young adults. *BioMed Research International*, *5*. doi: 10.1155/2013/850424.

Holbein, M. A., & Redfern, M. S. (1997). Functional stability limits while holding loads in various positions. *International Journal of Industrial Ergonomics, 19*(5), 387–395.

Holmes, M., MacKinnon, S., Matthews, J., Albert, W., Mills, S., & Bass, D. (2005, July 31-August 5). *Motion induced interruptions during simulated ship motions.* Paper presented at the ISB XXth Congress – ASB 29th Annual Meeting, Cleveland, OH.

Horak, F. B., & Nashner, L. M. (1986). Central programming of postural movements: Adaptation to altered support-surface configurations. *Neurophysiology, 55*(6), 1369–1381.

Hue, O., Simoneau, M., Marcotte, J., Berrigan, F., Doré, J., Marceau, P., . . . Teasdale, N. (2007). Body weight is a strong predictor of postural stability. *Gait and Posture*, *26*(1), 32–38.

Johansson, R., Magnusson, M., & Fransson, P. A. (1995). Galvanic vestibular stimulation for analysis of postural adaptation and stability. *IEEE Transactions on Biomedical Engineering*, *42*(3), 282–292.

Keshner, E. A., Allum, J. H. J., & Pfaltz, C. R. (1987). Postural coactivation and adaptation in the sway stabilizing responses of normals and patients with bilateral vestibular deficit. *Experimental Brain Research*, *69*(1), 77–92.

Ku, P. X., Abu Osman, N. A., Yusof, A., & Wan Abas, W. A. B. (2012). Biomechanical evaluation of the relationship between postural control and body mass index. *Journal of Biomechanics*, *45*(9), 1638–1642.

Langlois, R. G. (2010). Development of a spatial inverted pendulum shipboard postural stability model. In O. Turan, J. E. Bos, J. Stark & J. L. Colwell (Eds.), *International Conference of Human Performance at Sea (HPAS) 2010* (pp. 137–148). Glasgow, UK: University of Strathclyde.

Lanska, D. J., & Goetz, C. G. (2000). Romberg's sign: Development, adoption, and adaptation in the 19th century. *Neurology*, *55*(8), 1201–1206.

MacKinnon, S. N., Matthews, J., Holmes, M., & Albert, W. J. (2011/2012). The effect of platform motions upon the biomechanical demands of lifting tasks. *Occupational Ergonomics*, *10*, 103–112.

Matthews, J. D., MacKinnon, S. N., Albert, W. J., Holmes, M., & Patterson, A. (2007). Effects of moving environments on the physical demands of heavy material handling operators. *International Journal of Industrial Ergonomics*, *37*, 43–50.

McCauley, M. E., & Matsangas, P. (2005, 9-10 November). *Ship's motion effects on crew performance: A preliminary analysis of motion induced effects on high speed vessel (HSV).* Paper presented at the Network Centric Warfare Conference 2005, Athens, Greece.

McCauley, M. E., Matsangas, P., & Miller, N. L. (2005). *Motion and fatigue study in high speed vessel operations: Phase 1 report*. Monterey, CA: Naval Postgraduate School.

McCauley, M. E., Pierce, E. C., & Matsangas, P. (2007). The high-speed Navy: Vessel motion influences on human performance. *Naval Engineers Journal, 119*(1), 35–44.

McCauley, M. E., Pierce, E. C., Matsangas, P., Price, B., LaBreque, J., & Blankenship, J. (2007). *Vessel motion effects on human performance aboard the FSF-1 Sea Fighter*. Monterey, CA: Naval Postgraduate School and NSWC Panama City Division.

McDermott, K., Shaw, C., Demchak, J., & Holbein, M. A. (2005, 26-30 September). *Validity of functional stability limits as a measure of balance in adults ages 23 - 73.* Paper presented at the Human Factors and Ergonomics (HFES) Society 49th Annual Meeting, Orlando, FL.

McGinnis, P. (2013). *Biomechanics of sport and exercise*. (3rd ed.). Champaign, IL: Human Kinetics.

Morrison, T. R., Dobie, T. G., Willems, G. C., Webb, S. C., & Endler, J. L. (1991). *Ship roll stabilization and human performance*. New Orleans, LA: Naval Biodynamics Laboratory.

Nawayseh, N., & Griffin, M. J. (2006). Effect of frequency, magnitude and direction of translational and rotational oscillation on the postural stability of standing people. *Journal of Sound and Vibration*, *298*(3), 725–754.

Sari, M., & Griffin, M. J. (2009). *Subjective assessment of the postural stability of walking subjects exposed to lateral vibration*. Paper presented at the 44th UK Conference on Human Responses to Vibration, Loughborough University, Loughborough.

Southard, V., Dave, A., & Douris, P. (2010). Exploring the role of body mass index on balance reactions and gait in overweight sedentary middle-aged adults: A pilot study. *Journal of Primary Care and Community Health*, *1*(3), 178–183.

Stevens, S. C., & Parsons, M. G. (2002). Effects of motion at sea on crew performance: A survey. *Marine Technology and SNAME News*, *39*(1), 29–47.

Wedge, J., & Langlois, R. G. (2003, July). *Simulating the effects of ship motion on postural stability using articulated dynamic models.* Paper presented at the Summer Computer Simulation Conference (SCSC) 2003, Montreal, Canada.

Wertheim, A. H., Heus, R., & Vrijkotte, T. G. M. (1994). *Energy expenditure, physical workload and postural control during walking on a moving platform*. Soesterberg, The Netherlands: TNO Institute of Human Factors.

Wiker, S. F., & Pepper, R. L. (1978). *Change in crew performance, physiology and affective state due to motions aboard a small monohull vessel: A preliminary study*. Washington, D.C.: United States Coast Guard, Office of Research and Development.

Wilkins, R. H., & Brody, I. A. (1968). Romberg's sign. *Archives of Neurology*, *19*(1), 123.

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